HP3708A Noise and Interference Test Set

PRODUCT NOTE 3708-1

Noise and Interference Effects in Microwave Radio Systems

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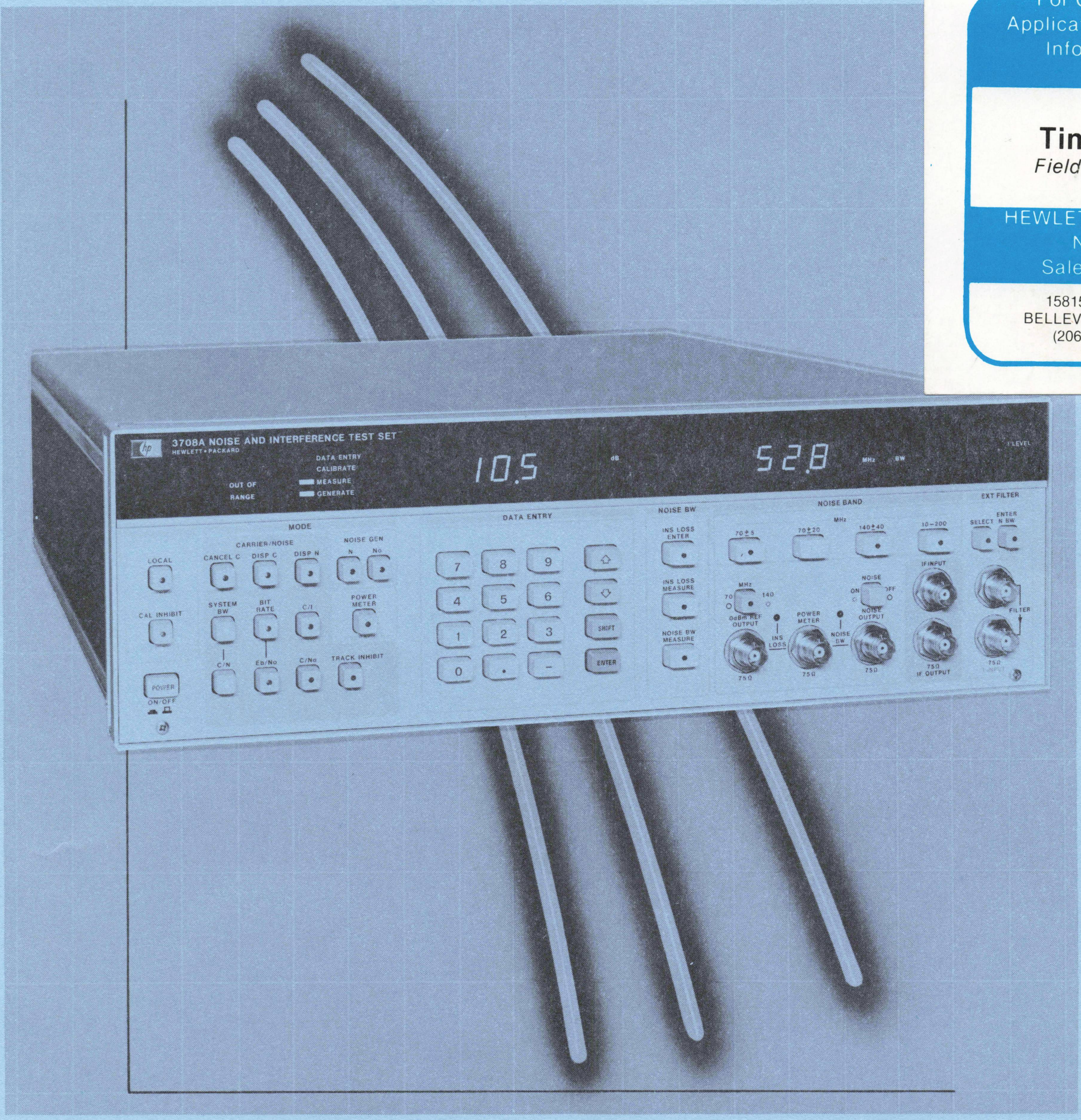

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CONTENTS

1. INTRODUCTION

An important characteristic of a microwave radio system is its ability to operate satisfactorily under non-ideal propagation conditions. Two of the most common (propagation related) causes of degradation on a microwave radio system are "FLAT FADING" and "INTERFERENCE".

Microwave flat fading occurs as a result of adverse climatic conditions, causing variation (usually reduction) in the level of the received RF carrier signal. As the carrier level decreases, the effect of the noise floor increases - ie the radio receiver "CARRIER TO NOISE RATIO" is reduced - and errors are induced on the digital system. Since the resultant effect is essentially the same, flat fade testing of microwave radios is also termed carrier to noise ratio, or C/N, testing.

Interference refers to the presence at the radio receiver of unwanted signals, commonly carriers from other microwave systems, which cause a reduction in the system's capability to deal with flat fades.

The extent of the performance degradation is measured differently on digital and analog microwave radio systems. On digital radios, the common measure of performance is the characteristic C/N versus BER curve. For analog radios, the measure is the characteristic C/N versus $(S/N)_{BB}$, or NPR, curve.

Traditional flat-fade testing (or C/N testing), involves the use of waveguide attenuators and power meters. This method is inaccurate under field operating conditions, and always awkward to perform. Traditional methods of interference testing suffer from similar problems. Now the HP 3708A Noise and Interference Test Set, adopting a different approach to C/N testing, allows flat-fade and interference testing to be performed quickly, easily and accurately, both in the factory and under field operating conditions.

This Product Note introduces the concepts of microwave radio noise, carrier to noise ratio (C/N), and interference in Sections 2 and 3. Section 4 discusses in detail the effect of flat-fading and interference conditions on the BER performance of digital radios, while Section 5 covers the same ground for the S/N_{BB} performance of analog radios. Finally in Section 6, a comparison between the traditional and HP 3708A methods of C/N testing is presented along with guidance on how to obtain the same results from both methods.

Although some background information is included in this Product Note, a basic knowledge of microwave radio design and operation is assumed. Tutorial texts on analog radio design/operation are widespread and commonly known, having been in print for many years. For further information, however, on the newer technology of digital radio refer to the following publications:

Feher, K: "Digital Communications Microwave Applications" (Prentice Hall Inc., 1981).

Bellamy, J.C.: "Digital Telephony" (Chapter 6) (John Wiley & Sons, 1982).

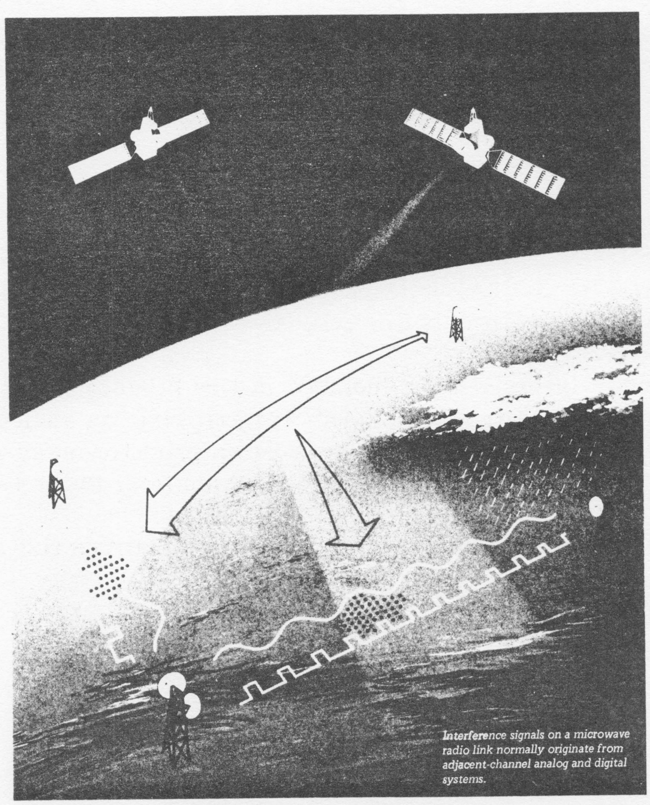
2. NOISE PARAMETERS

2.1 WHAT IS NOISE?

Electrical noise can be described as an unwanted signal which is always present in a communication system. Its presence impedes the reception of the wanted signal and is usually the limiting factor in its detection. Noise and interference play similar roles in communication systems, but they are dissimilar in nature.

Noise is composed of randomly-occurring voltages which are unrelated in phase or frequency and can have large amplitude peaks. Natural sources of noise include circuit noise, cosmic radiation and atmospheric disturbance. (See next page.)

Interference, or "man-made noise" arises mainly from electrical/electronic equipment which produce noise-like signals, but very often with regular properties. In a microwave radio system, the main type of interfering signal is similar to the desired signal. Modulated carriers at the same frequency or in adjacent channels represent primary sources of interference. A common example is the strong carrier component of an FM radio interfering under certain propagation conditions with other digital or analog radio systems.



Interference signals on a microwave radio link normally originate from adjacent-channel analog and digital systems.

Fig 1

As stated before, natural sources of noise include circuit noise, cosmic radiation and atmospheric disturbance. Circuit noise is due to the nature of electronic components and cannot be eliminated, only reduced by low-temperature operation. Examples of circuit noise include thermal noise (due to the random motion of electrons) and semiconductor shot noise (due to the random fluctuations in the diffusion of charge carriers).

The combined effect of cosmic and atmospheric noise is referred to as "SKY NOISE". Its relative effect across the microwave frequency band is shown below in Fig 2 but its absolute level is generally low compared to circuit noise in a microwave radio system.

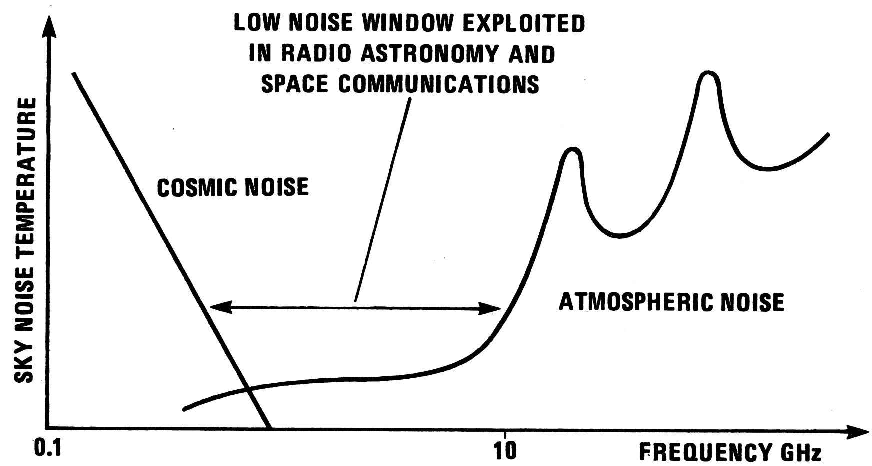


Fig 2

The performance of a microwave radio system is normally quoted at specific received carrier levels or received carrier-to-noise ratios. The level of noise in a radio receiver (due almost entirely to circuit noise) is determined by a number of system parameters including receiver gain, noise figure and bandwidth.

NOTE: Noise Temperature
A common method of quoting the power of a noise source is in terms of its (thermal) NOISE TEMPERATURE. If an electric conductor were perfectly insulated from the external environment there would still be noise present caused by the random motion of electrons; ie THERMAL NOISE. The thermal noise power affecting a given range of frequencies is proportional only to the absolute temperature and to the bandwidth of frequencies in question:

ie: $P_N = kTB$

where: P_N = Noise power in watts
k = Boltzmann's constant
T = Temperature in degrees Kelvin
B = Bandwidth in Hertz

The NOISE TEMPERATURE of a noise source is that temperature which would produce the equivalent thermal noise power over the same frequency range.

2.2 NOISE POWER AND BANDWIDTH

Noise level is normally quoted as being a specific RMS voltage developed across a known resistance, which then leads to the expression of noise power, P_N:

$$P_N = (V_{RMS})^2/R \qquad \text{where R is the cicuit resistance}$$

To define a noise signal it is necessary to state at least two parameters.

(i) The NOISE POWER (normally quoted in dBm)

(ii) The NOISE BANDWIDTH (normally quoted in Hertz)

The first of these can be easily measured using a broadband power meter whose bandwidth exceeds the bandwidth of the noise under test. The second requires the concept of NOISE BANDWIDTH to be introduced, since this is not necessarily the same as the simple 3 dB bandwidth normally used in electronics. Consider the following simplified diagram of a microwave radio receiver.

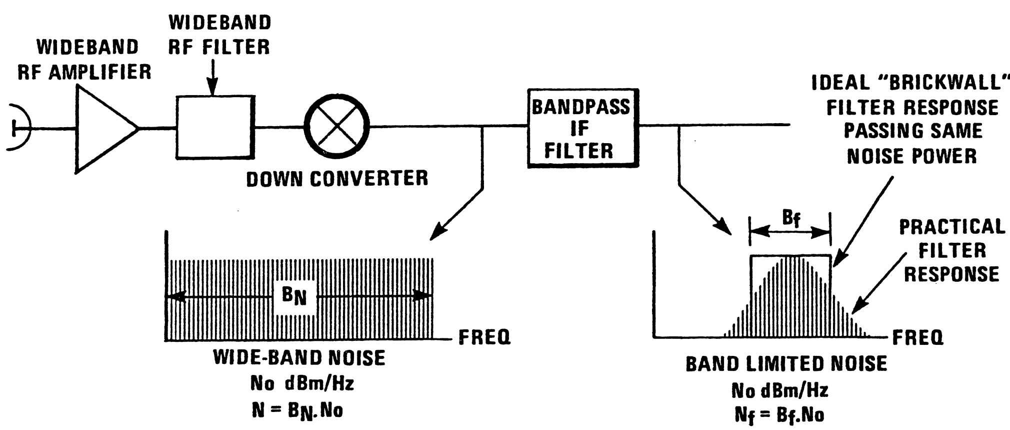


Fig 3

At the IF filter input, some amount of carrier power, C, and noise power N will be present. This noise power will be spread over a large but finite frequency range and will have a given bandwidth (B_N) and noise density (N_O) - ie noise level expressed as the power per 1 Hz bandwidth. At the IF filter output - assuming zero insertion loss for simplicity - the carrier power will still be C. The noise density will likewise remain unaffected, but the total noise power will be reduced by the band-pass effect of the filter. The bandwidth (B_f) of an ideal "brick-wall" filter which would deliver the same total noise power as the practical radio IF filter, is defined as the practical filter's "noise bandwidth."

NOTE: Bandwidth Independent Carrier to Noise Ratios
The noise power at the filter output will be:

$$N_f = B_f * N_O \quad \text{(ie Noise Power = Filter Noise Bandwidth x Noise Density)}$$

At the filter input, the noise power is given by: $N = B_N * N_O$ which is greater than N_f. Thus, the carrier to noise ratio at the filter input is different to the carrier to noise ratio at the filter output. Bandwidth independent carrier to noise ratios based on noise density, N_O, (eg C/N_O and Eb/N_O) are therefore commonly used since the results obtained are quoted independent of bandwidth. (See Section 3.2.)

2.3 NOISE QUALITY (THE GAUSSIAN DISTRIBUTION)

The receiver of a microwave radio system has at its input the desired radio signal and undesired interference signals. Noise is then added from the "Front End" components of the receiver (see Section 4.2.1, later). The result is a composite signal which is partly random in nature. Because of this random element, probabilistic techniques have to be used to predict the performance of the radio system. One of the most important statistical properties of a random variable is its probability of having a specified value (indicated by its Probability Density Function or PDF) or its probability of being within a specified range (indicated by its Cumulative Probability Density Function or CPDF).

The Gaussian Distribution PDF is a highly accurate repiesentation of the "front-end noise" of radio receivers. This makes it the most frequently used PDF for the prediction of microwave system performance. A full mathematical treatment of the Gaussian Distribution can be found in many text books, the following is only a simplified overview.

Consider Fig 4a which shows the "standardized" Gaussian PDF, P(x). This assumes no DC component and a RMS value of unity (ie $\sigma = 1$). Its mathematical expression is of the form:

$$P(x) = \frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}}$$

The shaded area of Fig 4a represents the probability of the value of x lying between 0.60 and 1.00 (ie between 0.6σ and 1.0σ).

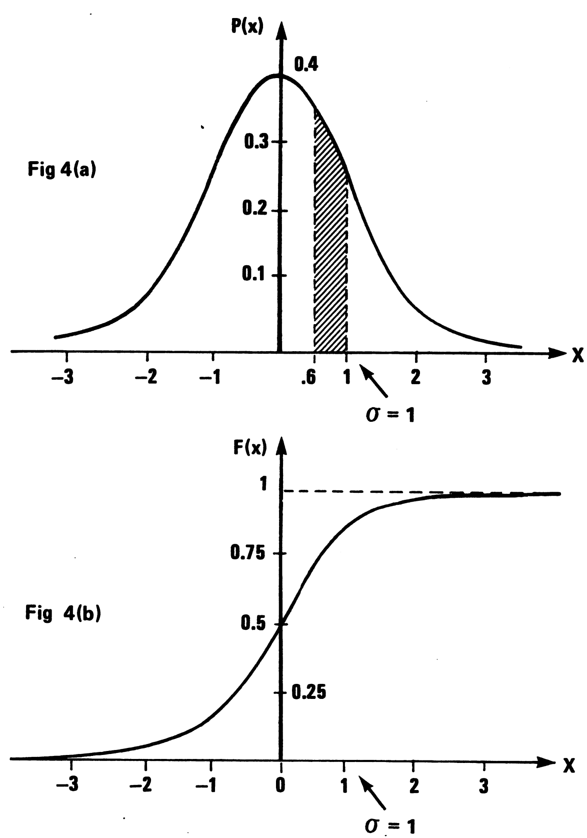


Fig 4

From the PDF we can determine the Cumulative Probability Distribution Function, (CPDF). The CPDF, F(X), is the total fractional area of the PDF, P(x), below the value of x = X (eg for X = 0 in Fig 4b, the CPDF equals 0.5 and is the fractional area to the left of x = 0 in the PDF graph).

The CPDF (shown in Fig 4b) corresponding to the standard Gaussian PDF is given by:

$$F(X) = \int_{-\infty}^{X} P(x)\,dx = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{X} e^{-\frac{x^2}{2}}\,dx$$

Applying this function to microwave receiver front end noise, this is the probability of the radio receiver instantaneous noise amplitude being less than a specified value "X". This function cannot be expressed in terms of elementary functions and it is usually related to the error function, erf(v), which has been numerically computed and tabulated.

An alternative function, the Complementary Cumulative Probability Density Function, provides the probability of a random variable (eg noise) being greater than a specified value. This complementary CPDF is plotted on a logarithmic scale in Fig 5 below, (along with the complementary error function):

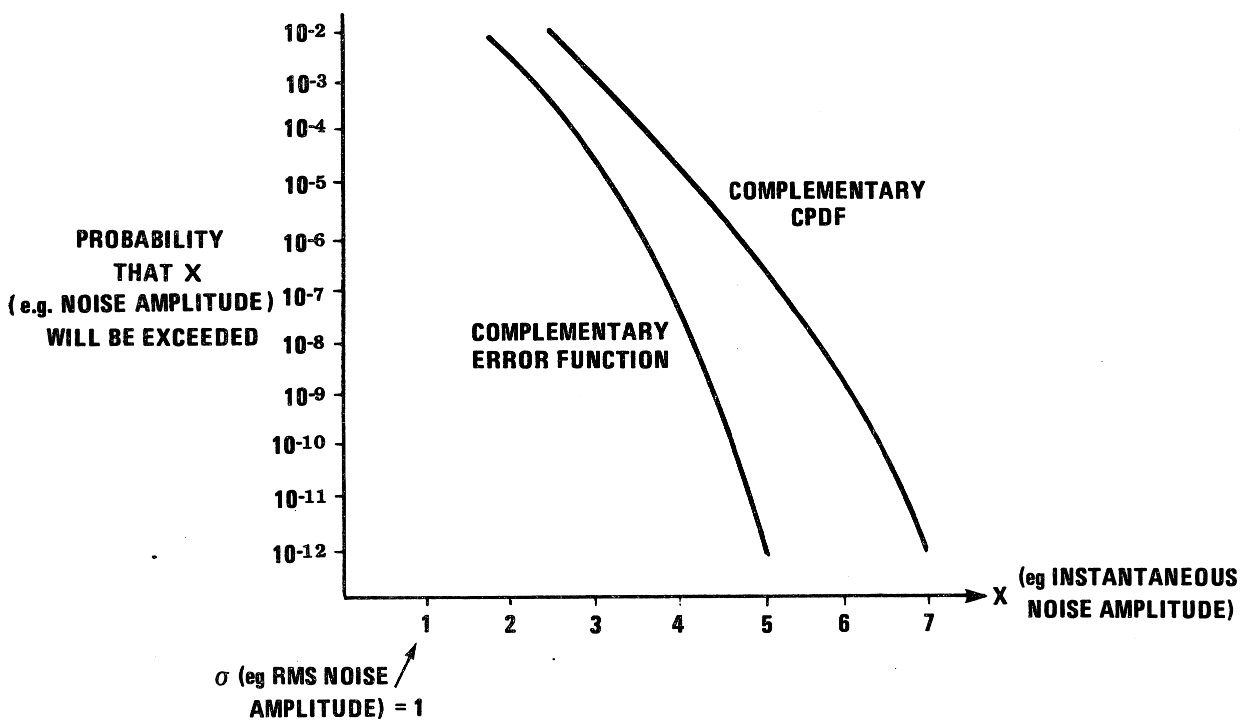


Fig 5

From this graph, we can see that the probability of an instantaneous noise amplitude value exceeding n times its RMS value decreases rapidly as n increases (1, 2, 3, . . .). Theoretically, ideal gaussian noise has infinitely high peaks. That is, there is a finite probability of very high (instantaneous) amplitude values occurring. Practical noise generators will follow the Gaussian distribution up to some maximum amplitude value, above which clipping will occur. This maximum level is normally specified in terms of the Crest Factor of the noise generator and is an important instrument parameter. Crest factors above 15 dB correspond to instantaneous peak amplitudes greater than 5 times the RMS value and give satisfactory approximation to Gaussian noise.

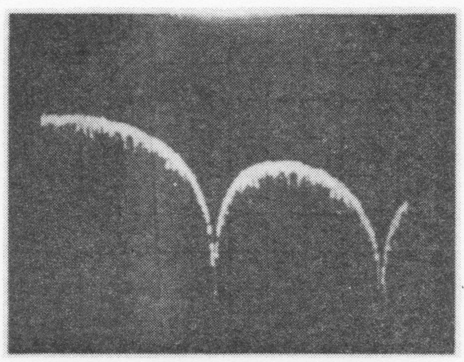
3. MICROWAVE RADIO CARRIER TO NOISE RATIO

3.1 DEFINITION OF CARRIER TO NOISE RATIO

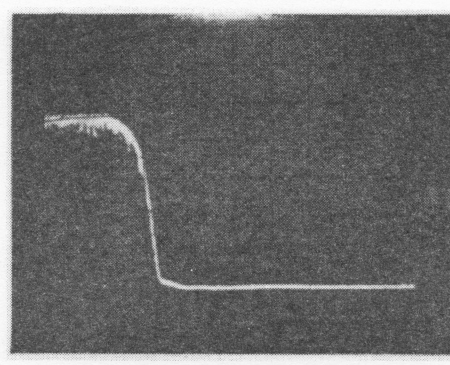
In microwave radio applications the term "Carrier to Noise Ratio" is used freely with little regard given to its proper meaning. Carrier to noise ratio properly defined is the ratio of the unmodulated IF carrier power to IF noise power. Note that the unmodulated IF carrier power and the received IF signal power with modulation (S_{IF}) may not be the same (ie C/N and S_{IF}/N may not be the same).

Consider for example an analog FM system employing a low modulation index. In this case there is generally little attenuation of the modulation sidebands by the transmitter/receiver filters, and, anyway, most of the signal power is contained in the carrier component. For such a system therefore, the S_{IF}/N ratio and C/N ratio are approximately the same.

On the other hand, however, a digital radio using Phase Shift Keying (PSK) or Amplitude Phase Shift Keying (APSK) has no identifiable carrier component and the transmitted signal conforms to a (sin x/x) spectrum over a theoretically infinite bandwidth. A practical system must limit this bandwidth and thus truncate the spectrum (see Fig 6). In this case the received IF signal power with modulation will be less than the unmodulated carrier power.



INFINITE BANDWIDTH



BAND LIMITED BY α = 0.3 FILTER

Fig 6

In C/N testing, the injected noise (ie C/N ratio) may sometimes be referenced to the unmodulated IF carrier power and sometimes to the modulated IF signal power. It is therefore important when comparing results to ensure that the carrier "reference term" is the same.

For simple PSK modulation, the (unmodulated) carrier power can be measured by removing the modulation, or clocking at a low symbol rate so that the major sidebands are all contained within the system bandwidth (ie filter passbands). With APSK or Quadrature Amplitude Modulation,(QAM), as it is commonly known, the situation is complicated because of the amplitude modulation and the received signal peak-power is higher than the average power; eg with 16 QAM, peak power is theoretically 2.7 dB higher than average power. For QAM modulation, therefore, the approximate unmodulated carrier (peak) power can be measured by clocking at a low symbol rate and taking into account the appropriate peak to average power ratio factor.

Here-after when the term Carrier to Noise ratio (C/N) is used, we will in fact be referring to S_{IF}/N since this "interpretation" is the most widely used and accepted.

The HP 3708A has been designed with maximum flexibility in defining the carrier power to take account of the differing requirements.

(i) "TRACKING MODE": Here the instrument references the C/N ratio to the continuously measured RMS signal power at the IF Input. Practically this is the most useful operating mode as it avoids inaccuracies due to varying received carrier level. The generated "C/N" values will however differ from the "unmodulated C/N" by a fixed offset which is a function of the modulation scheme and the filtering design of the radio.

(ii) "TRACK-INHIBIT MODE": In this case the instrument references the C/N ratio to the last carrier power measurement performed before the track-inhibit mode was selected. This allows for example the C/N ratio to be referenced to the unmodulated carrier power: - ie by performing an IF carrier power measurement with no modulation applied and then inhibiting the tracking operation (see below), the C/N ratio generated will there-after be referenced to the unmodulated carrier level. Any subsequent variations in the received signal level, however, will <u>not</u> be "Tracked" by the injected noise level.

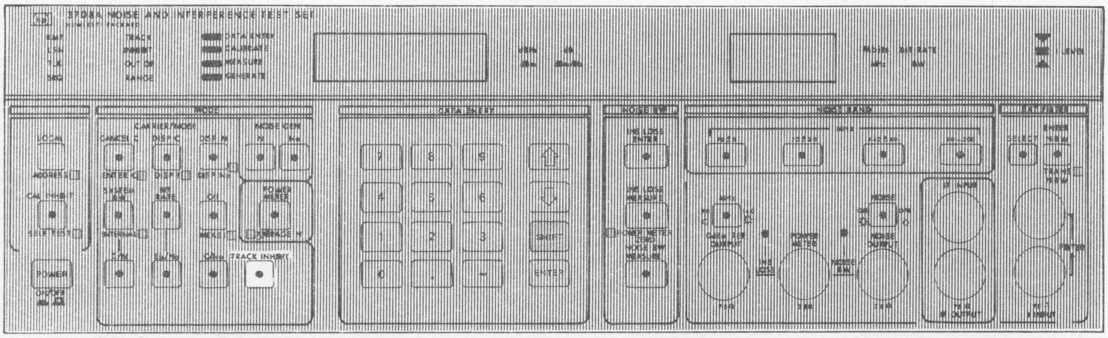


Fig 7

(iii) "ENTER C MODE": This allows the C/N ratio to be referenced to a carrier power level entered numerically via the instrument keyboard. This mode is of use where either carrier level measurement is not possible using the HP 3708A (eg in a burst mode application) or where carrier level measurement using the HP 3708A also involves some numerical calculation (eg measurement of QAM unmodulated carrier power via low symbol rate clocking). Note that when operating in this mode the tracking capability is automatically inhibited.

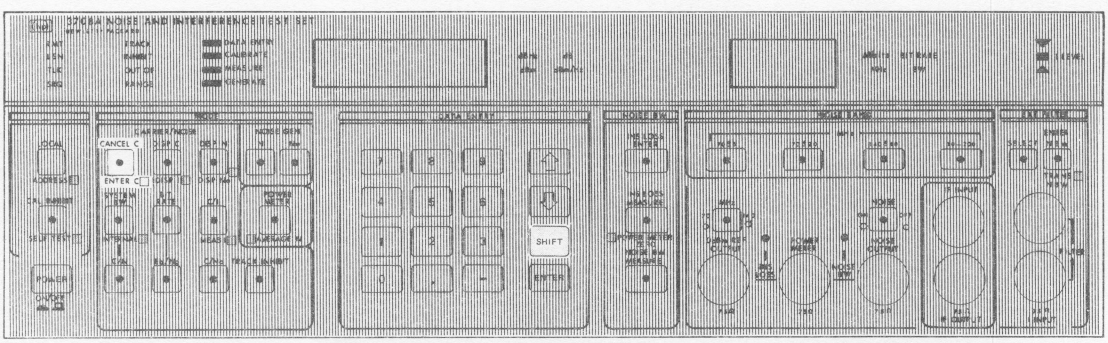


Fig 8

3.2 CARRIER TO NOISE RATIO UNITS

The most common unit used is Carrier power to Noise power (ie C/N). Quoted results using C/N units, however, must be treated with caution since the instrument generated C/N ratio may differ from that C/N value presented to the demodulator (due to radio filtering after the measurement point altering the effective noise bandwidth and hence total noise power - see Section 2.1). For this reason C/N results should always be reported with the associated measurement noise bandwidth. Alternatively, Carrier power to Noise Density (C/N_o) or Energy per-bit to Noise Density (Eb/N_o) are used. These last two ratios are based on noise (power) density (ie noise power per 1 Hz bandwidth) and, thus, any results may be quoted independent of the actual noise bandwidth of the system under test. The HP 3708A has been designed with maximum flexibility in the choice of C/N units, offering all of the above: ie C/N, C/N_o, and Eb/N_o.

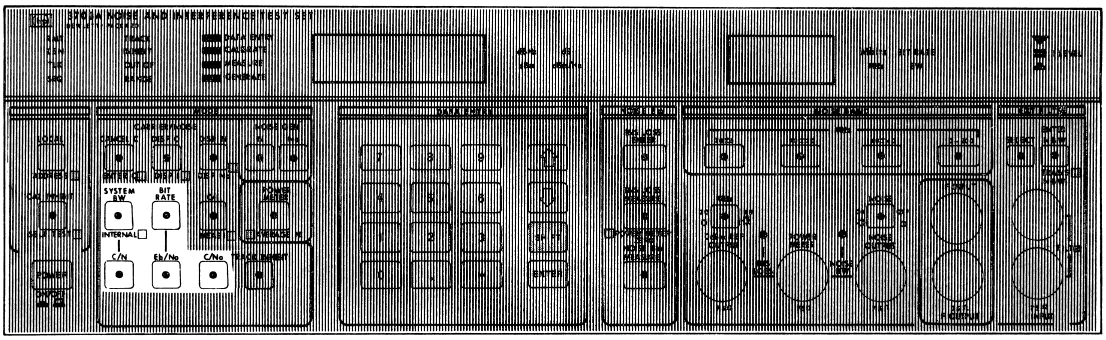


Fig 9

(i) C/N UNITS (dB): With these units the noise bandwidth of the generated noise should, if used correctly, be the radio receiver "system noise bandwidth"; ie the equivalent IF bandwidth of the narrowest filter in the receiver chain. For most analog radios the IF filter will determine the system noise bandwidth and therefore the noise power (and thus C/N ratio) should be defined in the bandwidth of this filter. This can be achieved with the HP 3708A by positioning the instrument prior to the IF filter and entering this filter's bandwidth as the "SYSTEM BANDWIDTH" on the HP 3708A - ie the HP 3708A compensates for noise power loss during filtering and effectively defines the C/N ratio at the output of the IF filter. (See Fig 10 below.)

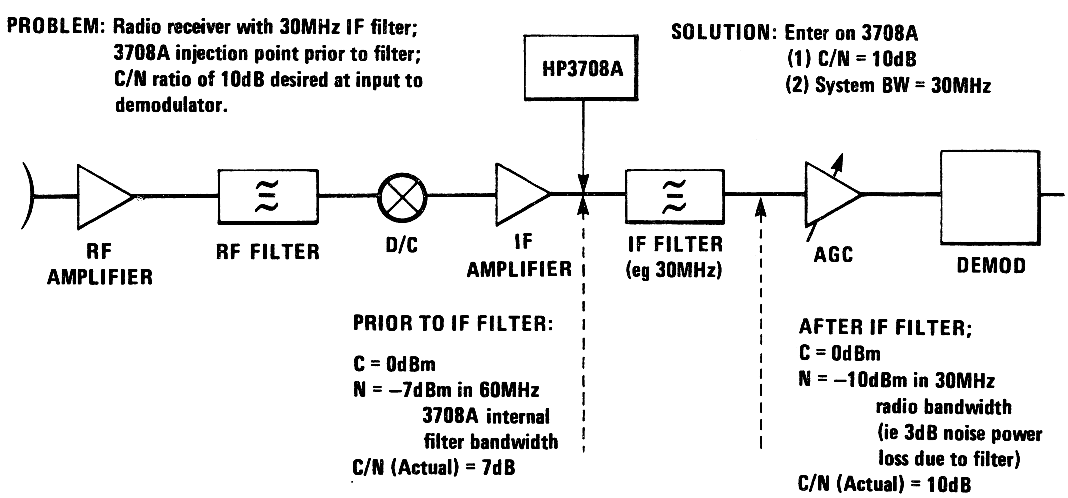


Fig 10

If no system noise bandwidth value is entered, then the generated noise power is defined in the noise bandwidth of the selected HP 3708A internal filter. This in effect means that the operator entered C/N ratio is defined at the IF OUTPUT connector on the instrument and not at the output of the system noise-bandwidth limiting filter. Where access to the radio IF section is possible only after the radio IF filter, by use of the EXTernal FILTER facility of the HP 3708A and an identical filter to that in the radio itself, the C/N ratio may still be defined for the noise bandwidth of the radio receiver. Digital radios, however, normally have baseband filtering (prior to the decision circuitry) of an equivalent (if not narrower) bandwidth to that of the IF filter. In these cases, the equivalent IF (ie double sided) noise bandwidth of the baseband filtering should be entered as the SYSTEM BANDWIDTH. Note also that in these cases the HP 3708A may be positioned either before or after the radio IF filter with no requirement to use the EXTernal FILTER facility.

An additional use of the EXT FILTER facility is for microwave radio customers who perform C/N testing with the noise defined in a very narrow bandwidth, much narrower than any filter in the radio receiver. This ensures that all the noise power passes through the radio receiver chain to the demodulator input (ensuring that the selected C/N ratio is independent of system bandwidth) and can be achieved with a suitable filter connected across the EXT FILTER ports.

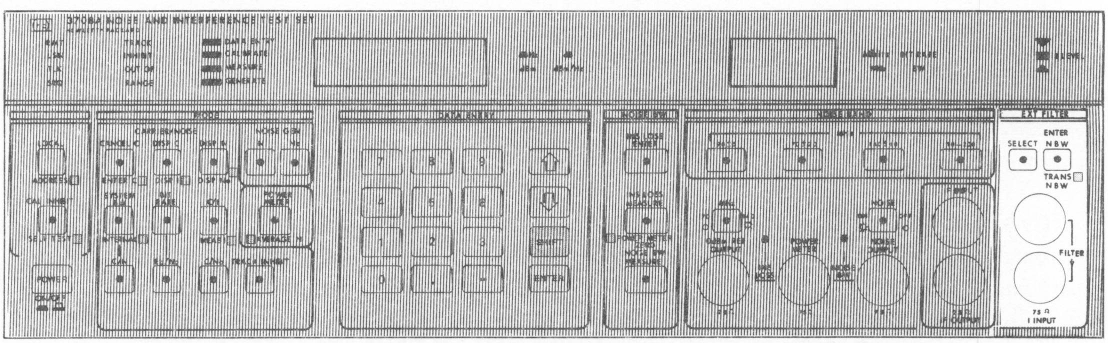


Fig 11

(ii) C/N_0 UNITS (dB Hz): No system noise bandwidth entry is required for these units since the noise level in defined as a power density (ie relative to a 1 Hz bandwidth). Noise density, N_0, remains unchanged (relative to the carrier power) throughout the radio receiver chain since any radio filtering affects only noise bandwidth (not level) and hence only total noise power. Even with C/N_0 units, however, the HP 3708A must still be positioned prior to the system bandwidth defining filter in the receiver chain (and if this is not possible then the EXT FILTER facility must be used).

(iii) Eb/N_0 UNITS (dB): With these units the carrier power is expressed in terms of energy per bit (ie carrier power divided by bit rate). As the HP 3708A has no means of determining the baseband bit rate of the radio under test this bit-rate value must be entered numerically via the keyboard. Eb/N_0 is used extensively in satellite radio systems. When using Eb/N_0 units, the same rules apply to the positioning of the HP 3808A as for C/N_0 units.

NOTE: Useful Expressions

(i) (C/N_0) dB Hz $=$ (C/N) dB $+ 10 \log_{10} B$ where B = System Noise Bandwidth in Hz

(ii) (Eb/N_0) dB $=$ (C/N) dB $+ 10 \log_{10} (B/f_b)$ where f_b = System Bit Rate in bits/s

4. NOISE AND INTERFERENCE EFFECTS IN DIGITAL RADIO SYSTEMS

4.1 DIGITAL RADIO DESCRIPTION

The ultimate performance indicator of any digital transmission system is its error ratio, or more accurately, its error probability. Under normal operating conditions, the received carrier level in a digital radio is sufficiently high (ie high C/N ratio) to give a very low error probability with values better than 10^{-10} (ie residual or background BER). Under carrier flat fading conditions of sufficient severity, however, (ie low C/N ratios) the BER performance of the digital system will degrade rapidly to unacceptable levels. The point at which this degradation commences, the rate of degradation thereafter and the residual BER at high C/N ratios are obviously important performance parameters of the radio system. These parameters are determined by the radio design/adjustment and the presence of other propagation impairments on the link, eg interference. Potential sources of non-optimum performance in the design/adjustment of the radio system include bad equalization, clock phase errors, timing jitter, MODEM phase/amplitude errors, and (amplifier) non-linearity.

C/N vs BER testing is thus an important procedure in the manufacturing, commissioning and maintenance of digital microwave links to check system performance and aid in the identification of impairments and the optimum adjustment of the radio.

To understand exactly what happens at a digital radio receiver during carrier fading and interference conditions consider first the simplified block diagram of a digital radio shown below.

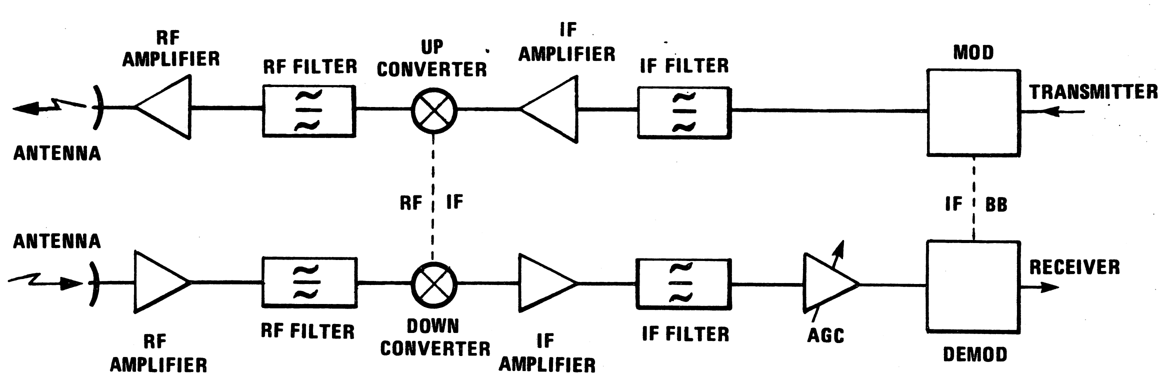


Fig 12

At the transmitter IF and RF stages the modulated signal is up-converted to the appropriate propagation frequency (eg 6 GHz) and amplified to a sufficiently high carrier level (eg 40 dBm). Losses during propagation reduce this carrier level to a relatively low value at the receiver (eg in the range -75 to -25 dBm). Consequently, during the radio receiver RF and IF stages, as well as frequency down-conversion, the low received carrier level is amplified to a level suitable for demodulation. Receiver RF amplification is generally of fixed value (typically 25 dB) while the IF amplification varies due to the action of the AGC (Automatic Gain Control) which ensures that a constant carrier level (eg 1 dBm) is presented to the demodulator input.

4.2 ADVERSE RECEIVED CARRIER CONDITIONS

In this Section we shall describe in more detail the effects that:

(i) fading of the received carrier, and

(ii) interference on the received carrier

have on the IF signal eventually presented to the receiver demodulator.

4.2.1 Received Carrier Flat Fading Conditions

Consider first the level of noise in a microwave radio receiver. As stated before, the main source of noise in a radio receiver is circuit noise from the radio components themselves. Electronic network noise "levels" are normally quoted in terms of Noise Figures (F), ie the ratio of the actual noise output from the network to the theoretical minimum noise output (which depends only on the network temperature, bandwidth and gain):

$$\text{i.e. } F = \frac{N_{ACTUAL}}{k\ T_O\ BG} \qquad (1)$$

where: k = Boltzmann's constant
T_O = Network temperature (in degrees Kelvin)
B = Network noise bandwidth
G = Network gain

Now when networks are cascaded together to form a complex system (as for example in a radio receiver) the overall noise figure of the system, F_S, is given by the expression:

$$F_S = F_1 + \frac{(F_2 - 1)}{G_1} + \frac{(F_3 - 1)}{G_1 G_2} + \cdots\cdots + \frac{(F_n - 1)}{G_1 G_2 \cdots G_{n-1}} \qquad (2)$$

where: F_1 and G_1 are the noise figure and gain of the first network
F_2 and G_2 are the noise figure and gain of the second network etc.

The overall noise figure is thus determined by the noise figures of the first few networks in the system especially if the gains of these first few networks is large. Now, for a radio receiver, we stated that the gain of the RF stage is typically of the order of 25 dB and hence we may conclude that the overall noise figure of a radio receiver is determined by the first few components (or FRONT-END components) in the RF section of the receiver. In other words, any noise added from components subsequent to the RF section will be negligible in comparison to the RF added noise. Typical noise figures for digital radio receivers are in the range 4 to 10 dB.

Now at the output from the radio receiver RF stage the noise "level" (ie density), N_O, is given by (re-arranging expression (1) and omitting B since expressing noise level in terms of a density):

$$N_O = k\,T_O\,G_{RF}\,F \qquad (3)$$

where : G_{RF} = Receiver RF gain
F = Receiver noise figure

while the carrier level, C, is given by:

$$C = \text{Received RF Carrier Level} \times G_{RF} \qquad (4)$$

The C/N_o ratio at the output from the RF stage is thus determined by the received carrier level since all other factors in expressions (3) and (4) are constant for a given radio. This C/N_o ratio remains unchanged throughout the receiver IF stage since effectively no further noise is added and both "signals" (ie C and N_o) receive the same amplification (ie the absolute levels of C and N_o change but their relative ratio remains the same). The C/N_o ratio presented to the demodulator is thus the same as that present at the output from the RF stage and is determined by the received carrier level; ie the lower the received carrier level the lower the resultant C/N_o level. Note that the total noise power, N, (and thus C/N ratio) presented to the demodulator will depend on the receiver filtering (ie the system noise bandwidth).

The resultant effect of flat fading at the radio receiver is thus simply a variation (normally a reduction) in the carrier to noise ratio presented to the demodulator. Note, however, that due to the action of the AGC, varying C/N ratio at the demodulator appears to be caused by varying noise level with constant carrier and not by what is actually happening, varying carrier with constant noise level. In other words, to the radio demodulator, flat fading appears as increased receiver noise level. (See Fig 13.)

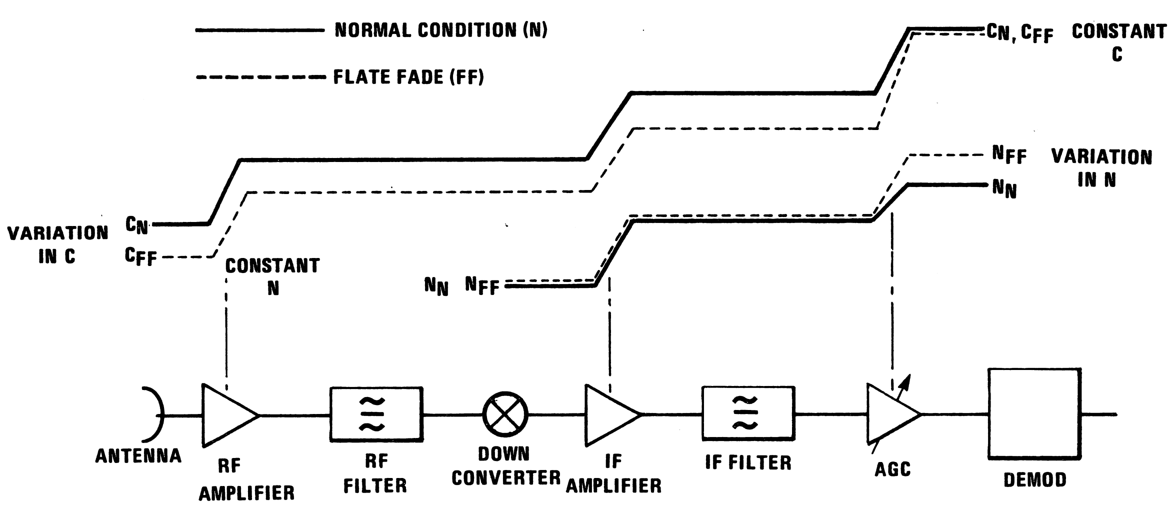


Fig 13

4.2.2 Received Carrier Interference Conditions

Any interference signal present at the receiver antenna will pass unaffected through the radio RF and IF sections to the demodulator provided that the interference signal spectrum is contained within the passband of the RF and IF filters. If this is not the case then the interference signal will suffer attenuation distortion proportional to the amount of out-of-band spectrum present. Assuming no attenuation distortion of the interfering signal occurs, the carrier to interference ratio (C/I) will remain unchanged throughout the RF and IF receiver chain since both signals will receive equal amplification.The above remains true regardless of whether the source of the interference is an analog radio (FM or AM) or another digital radio.

4.3 DIGITAL RADIO VISUAL PERFORMANCE INDICATORS

Before going on to explain how low C/N ratios and interference conditions (ie C/I ratios) at the input to the receiver demodulator result in the generation of errors in the digital data stream, we will first introduce the concepts of digital radio "EYE DIAGRAMS" and "PHASE STATE CONSTELLATIONS". The use of these concepts should then help in the understanding of the error generation mechanism.

4.3.1 Eye Diagram

The effects of noise and interference in digital radio demodulators may be evaluated by examining "eye diagrams" of the reconstructed symbol streams immediately before the demodulator decision (or slicing) process. These diagrams give a convenient display of the modulation states.

Eye diagrams may be thought of as viewing, on a storage oscilloscope, sections of a digital symbol pattern superimposed on top of each other. Consider for example Fig 14 showing the superimposition of various 3-symbol sections of a 2-level digital symbol stream - ie an (NRZ) binary data stream.

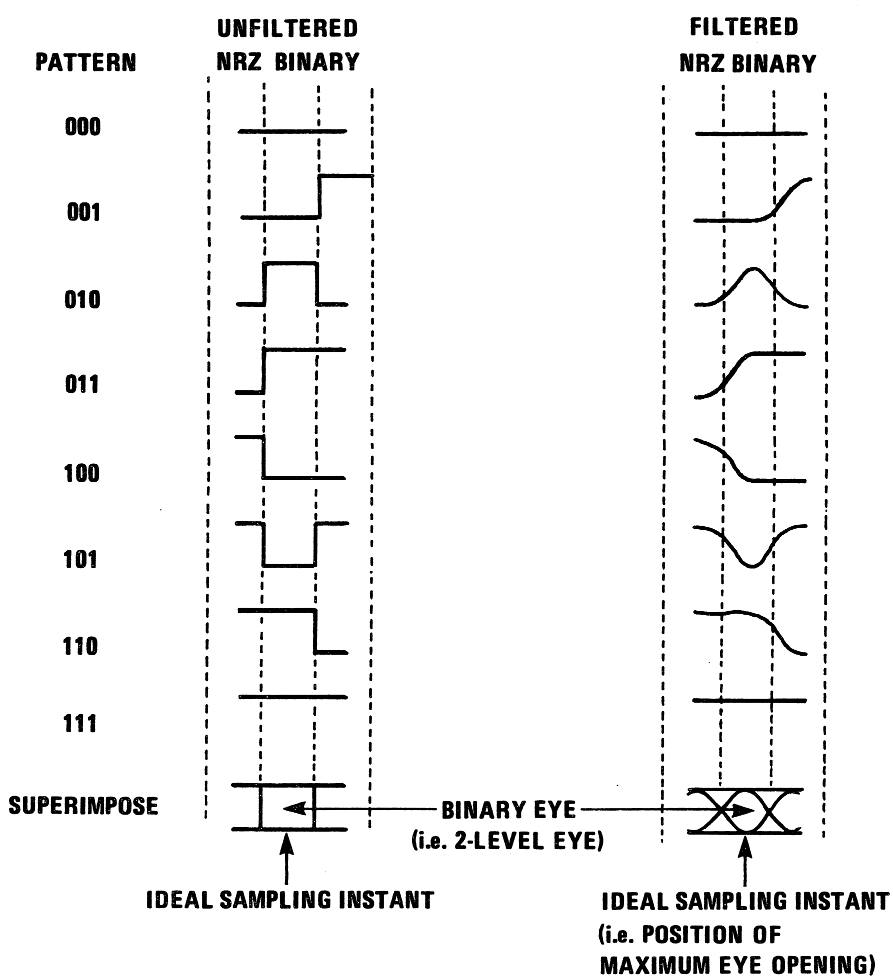
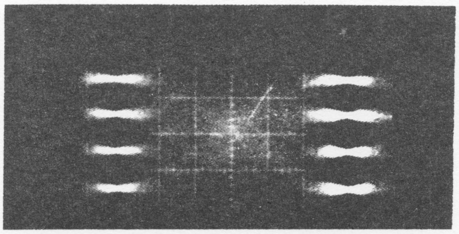
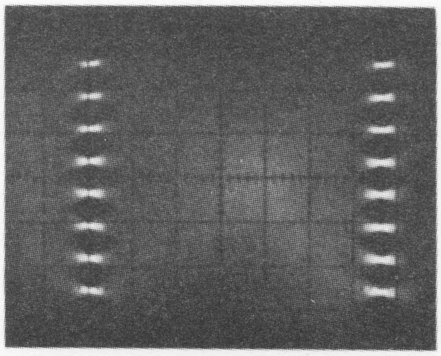


Fig 14

In digital radio systems the reconstructed symbol streams normally exhibit multi-level eye patterns - ie the input data stream (or divided data sub-stream) passes through a digital to analog converter where N data bits are considered at a time and converted into one of 2^N possible levels (or "symbols"). For example, shown below are the eye diagrams of a 16 QAM system (ie 4-level eye) and a 64 QAM system (ie 8-level eye) at normal (ie high) received carrier levels.



16 QAM EYE PATTERN

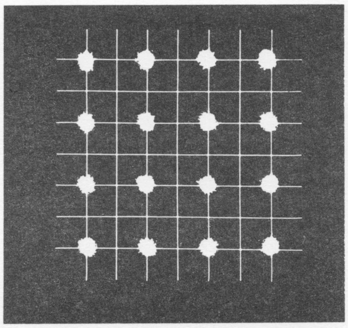


64 QAM EYE PATTERN

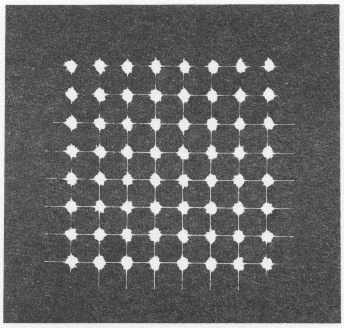
Fig 15

4.3.2 Phase State Constellation

An alternative representation used for phase and amplitude modulation schemes (eg QAM), is a display of the "phase state plane" or "constellation". This is simply a two-dimensional representation of the possible symbol states, with the In-phase and Quadrature-phase (I and Q) signal components used as axes, - ie sample, at the ideal instant, the multi-level eye patterns of both the I and Q symbol streams and apply the sampled levels to the X (ie I) and Y (ie Q) plates of a storage display thereby superimposing the sampled states. Shown below are typical constellations for a 16 QAM system (ie 4-level eye x 4-level eye) and a 64 QAM system (ie 8-level eye x 8-level eye) at normal (ie high) received carrier levels.



16 QAM CONSTELLATION



64 QAM CONSTELLATION

Fig 16

NOTE: Ideal Constellation

An ideal constellation, if this were possible, would consist of an array of infinitely small points since all samples of nominally the same state would have exactly the same value and would thus superimpose on top of each other. Even at normal (high) received carrier levels, however, the practical constellation consists of small clusters and not fine points. This is because all practical radios even at high received carrier levels contain residual (or inherent) intersymbol interference (ISI) and noise which effectively changes the symbol eye openings from their single theoretical value of 100% to continually varying levels of between - for example - 90 to 110%. Thus the sampled levels of nominally the same state show some variation and do not superimpose exactly on top of each other. (See QPSK example in Fig 17 below.) It is this residual ISI and noise which sets the limit on the lowest residual BER (ie BER at the normal high received carrier levels) that the radio can achieve.

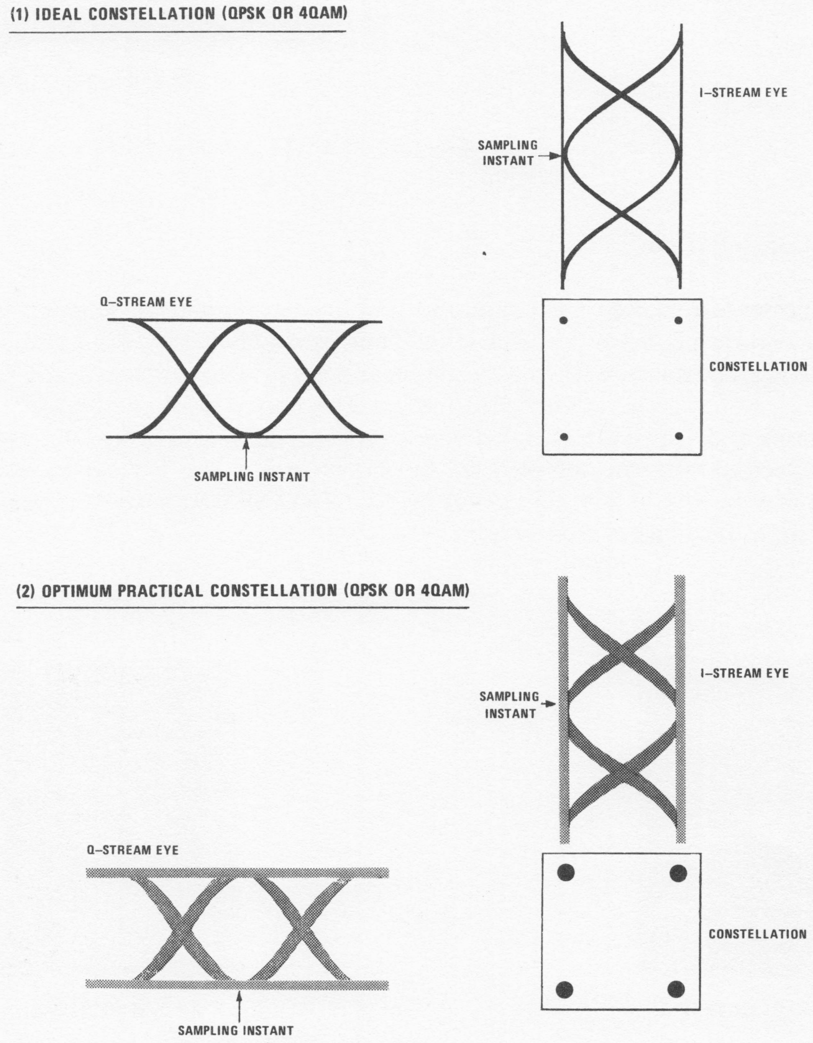


Fig 17

4.4 ERROR GENERATION IN DIGITAL RADIO DEMODULATORS DUE TO NOISE AND INTERFERENCE

4.4.1 Error Generation Mechanism

In a digital radio receiver, the ultimate determinant of system performance is the probability of error at the demodulator decision circuitry. A reconstructed symbol has to be identified as one of a possible set of defined symbols. In the simple binary case (as shown in Fig 18), a decision threshold will determine whether the received symbol (at the sampling instant) is detected as a "1" or a "0".

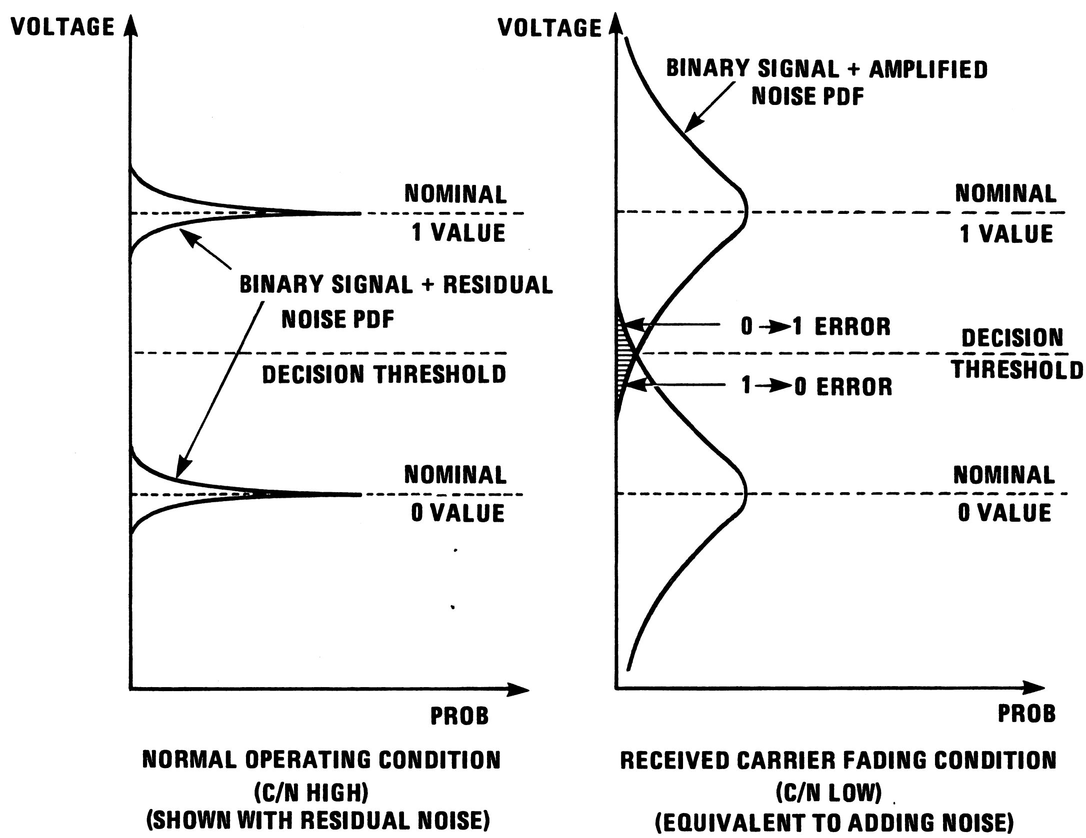


Fig 18

If the received carrier contains amplified noise due to received carrier fading (ie low C/N ratio) and/or interference, the reconstructed symbols will have this additional demodulated signal super-imposed on them and a continuum of levels will occur rather than the two allowed values. In the binary example shown above, some fraction of the "1" symbol PDF now extends below the slicing threshold and vice versa. This fractional area below the threshold can be evaluated from the CPDF of the "added" noise, allowing a determination of the expected symbol error probabilty. In other words, knowing the maximum tolerable noise peak (ie the voltage difference between the nominal decision level and the decision threshold) and the CPDF of the amplified noise (determined by the noise power) the probability of symbol error may be computed. Similarily for interference, knowing the CPDF of the added interfering signal and the maximum tolerable interference peak allows a determination of the expected symbol error probability.

The effect of the added noise and interference can be easily visualised by examining the constellations of the received signal immediately before the decision process. In Fig 19 below, the effect on the constellation of a 16 QAM radio for the following conditions is shown:

(i) Normal operating condition (ie high C/N)

(ii) Fading of received carrier level (ie low C/N)

(iii) Addition of sinusoidal (or FM) interference signal.

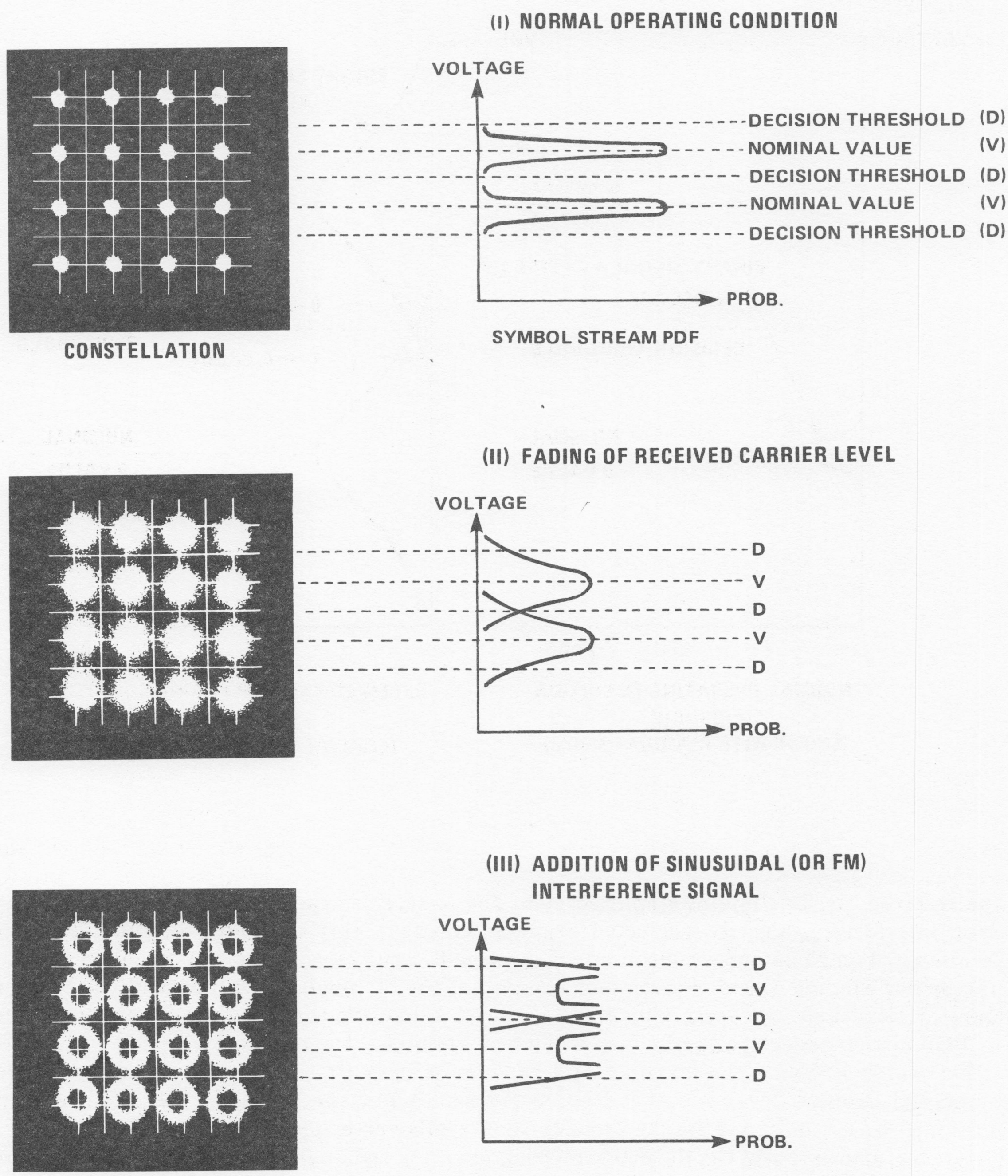


Fig 19

4.4.2 Flat Fading Performance

In the case of fading of the received carrier level (equivalent to adding noise) it was stated that knowing the maximum tolerable noise peak and the CPDF of the added noise would allow us to compute symbol error probability. Both of these required terms can be related, however, to the radio receiver C/N ratio and the modulation scheme being used. The symbol error probability (SER) can thus be computed for any given carrier to noise ratio and modulation scheme, assuming perfect (ie theoretical) implementation, eg no residual ISI/noise. Theoretical curves are shown below in Fig 20 for some common modulation schemes:

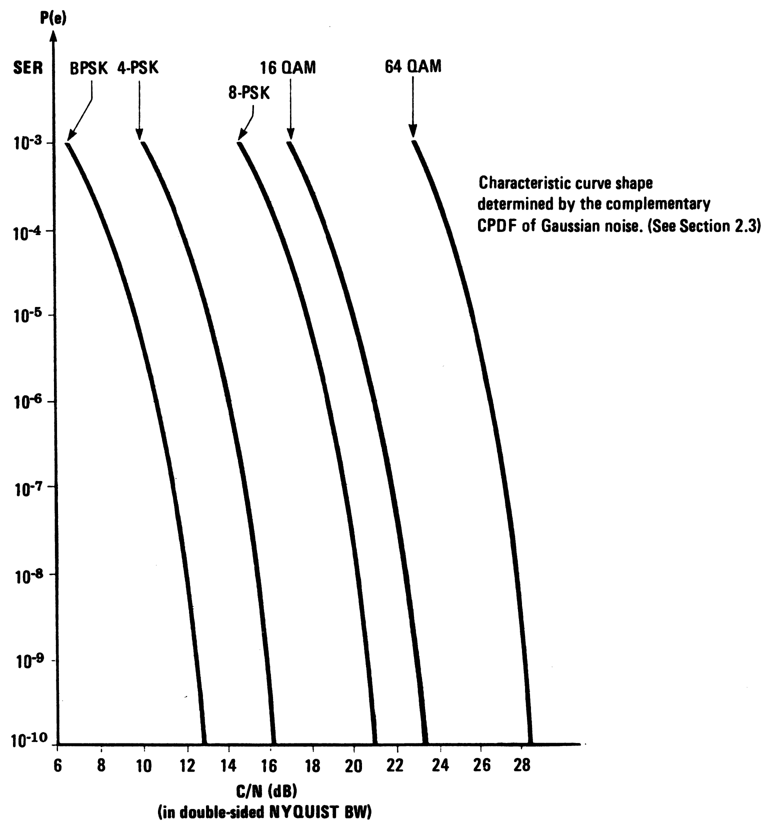


Fig 20

Theoretical C/N vs SER curves are normally quoted on the basis that the system (noise) bandwidth employed is the MINIMUM required for transmission of the signal. This minimum bandwidth, termed the "DOUBLE SIDED NYQUIST BANDWIDTH" is equal to the system symbol rate expressed in Hertz. (For this reason the Double Sided Nyquist Bandwidth is often called the Symbol Rate Bandwidth).

Example: For a 140 Mbit/s, 16 QAM (ie 1 symbol per 4 bits) system, the symbol rate is 35 MS/s and thus the Double Sided Nyquist Bandwidth is 35 MHz.

For technical reasons this minimum bandwidth is never achieved on practical radios (except those using special reduced bandwidth techniques). A comparison of the practical radio performance against that theoretically possible can be obtained with the HP 3708A, however, by defining the C/N ratio in the Double Sided Nyquist Bandwidth using the "SYSTEM BANDWIDTH" facility (see Section 3.2) while letting the radio filters define the actual noise bandwidth.

Fig 21 below shows typical C/N vs SER curves for practical radios along with the appropriate theoretical curve. Two practical curves are plotted, namely:

(i) for a "well aligned" practical radio (ie well designed, optimally adjusted radio).

(ii) for a "badly aligned" practical radio (ie badly designed and/or badly adjusted radio).

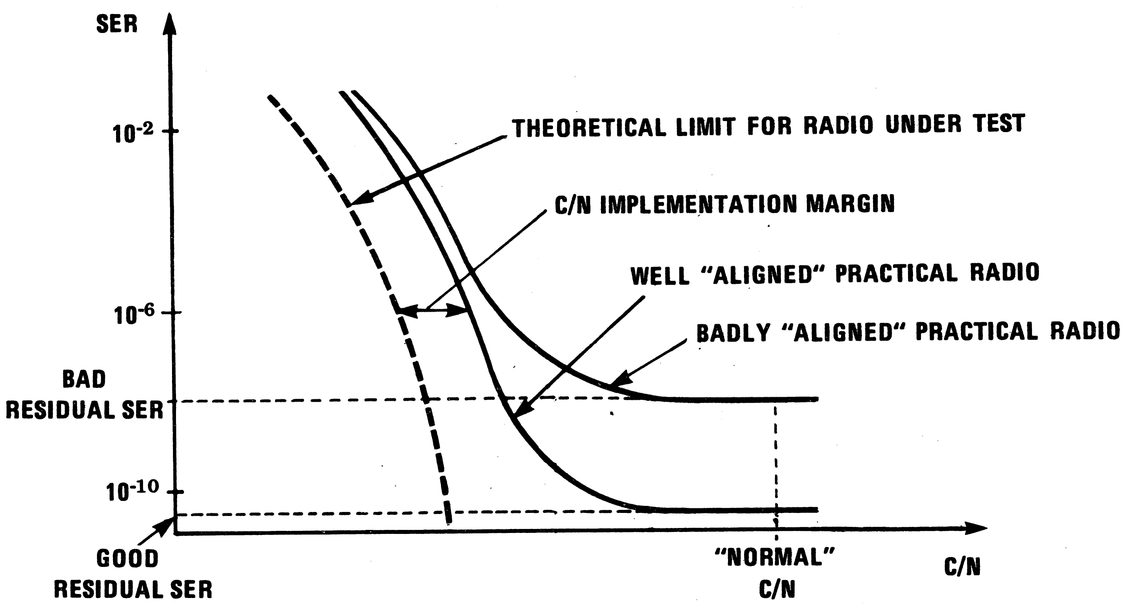


Fig 21

For the well aligned practical radio the performance curve is shifted to the right from that theoretically possible due to the practical implementation being non-perfect (as a result of technical and economic trade-offs). This shift is termed the "C/N Implementation Margin". There is also a tailing-off (at the low SER end) of the practical curve due to the inherent ISI, noise and other imperfections present in the practical system. The RESIDUAL SER of the well aligned practical radio (ie the SER at the normal (high) received carrier level) is, however, still at a very low level, being $<10^{-10}$.

For the badly aligned practical radio the overall performance is degraded from that of the well aligned system and the residual SER is now at an unsatisfactory level of $>10^{-10}$.

NOTE: Residual SER Determination
A measure of residual SER is often used as an indication of overall radio system alignment (ie adjustment). Traditional methods of measuring residual SER, however, require very long test times and thus are unsuitable for most applications. A quick method of estimating residual SER is possible using the HP 3708A and this method is described in Product Note 3708-3 (Publication Number 5953-5490).

4.4.3 Interference Performance

In a similar manner to that for flat fading, when an interference signal is present at the radio receiver the symbol error probability can be computed for any given carrier to interference ratio (C/I), knowing the modulation scheme employed and the nature of the interference signal. Shown below is an ideal (ie no intrinsic radio noise/ISI) C/I versus SER plot for a constant amplitude interferer (eg FM signal) along with a typical practical plot.

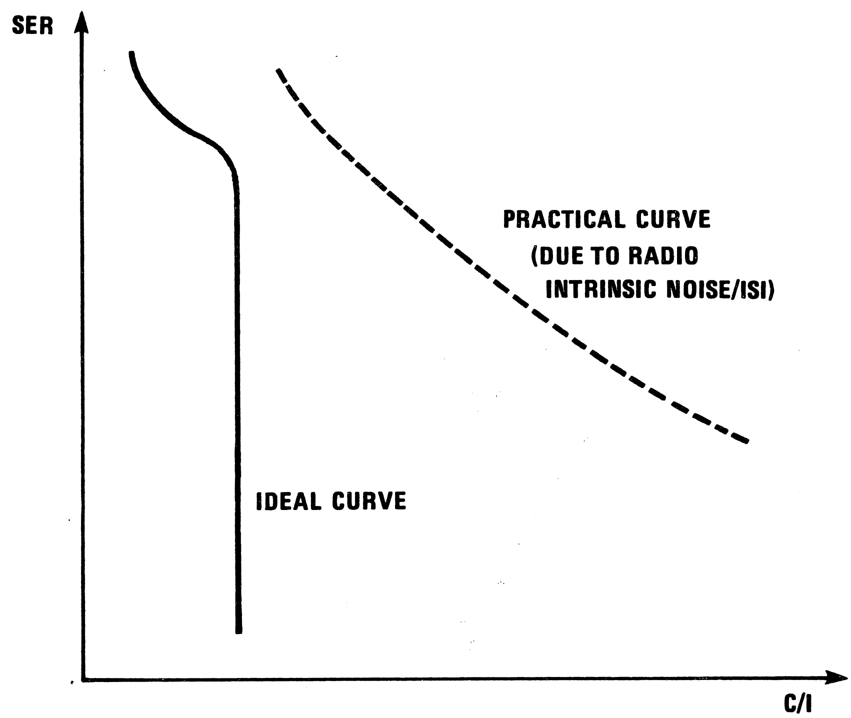


Fig 22

The vertical drop (or knee) in the ideal curve occurs (at that C/I ratio) when the peak amplitude of the demodulated interference signal (A_{pk}) just exceeds the distance from the nominal decision value to the decision threshold. The curve shape prior to the knee is determined by the fact that the SER is directly proportional to A_{pk} which in turn is inversely proportional to the square root of the C/I ratio.

ie $\quad SER \propto A_{pk}$

$$\propto \sqrt{2/(C/I)}$$

where: $I \propto (A_{pk})^2$

In practical measurements the "C/I knee" is never determined since the intrinsic radio noise/ISI "masks" the transition from high SER to zero SER.

4.4.4 Combined Flat Fading and Interference Performance

Up until now we have considered separately the effects of fading of the received carrier level (equivalent to adding noise) and the presence of undesired interference signals. In practice, however, these adverse propogation conditions may occur simultaneously and hence it is of great importance to determine the performance of the digital radio under these combined conditions. This is normally done by plotting a number of C/N versus SER characteristics for the radio under test with an interfering tone of variable strength also added (at IF or RF) to the desired signal. The strength of the interfering tone (normally quoted in terms of a C/I ratio) is increased between plots. The effect of the interference signal is to shift the C/N versus SER plot to the right as shown in Fig 23 below, the amount of shift being dependent on the strength of the interference signal and the radio performance (ie design/adjustment).

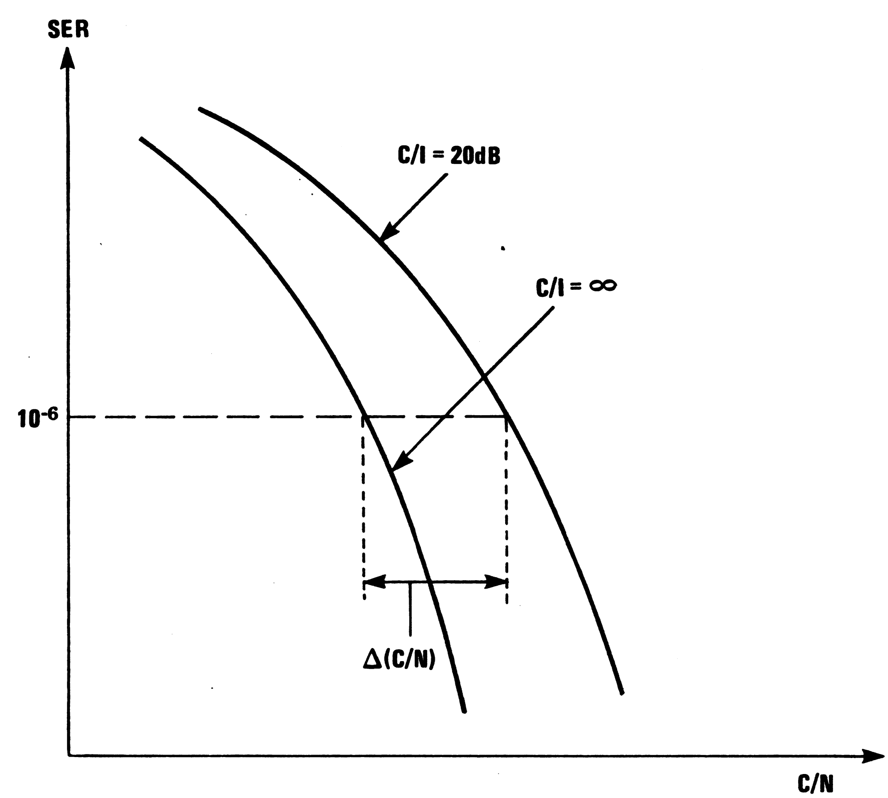


Fig 23

In the past the difference between two C/N values (measured for example at an SER of 10^{-6}) has often been used as a measure of overall radio performance. Radio operators during periodic maintenance would check the ΔC/N value for degradation from that value measured previously. The major benefit of this test method is that it is a relative comparison and the noise bandwidth of the radio need not be known (eg one specification will apply to all radios of the same modulation type regardless of system noise bandwidth).

NOTE: Conversion of SER to BER
[See Appendix B of Product Note 3708-3 (5953-5490) for more details.]

Having determined the symbol error probability (SER) for any given C/N (or C/I) ratio present at the input to the radio receiver demodulator the resultant bit error probability (BER) in the digital data output from the radio link may be determined from a simple relationship derived from the modulation scheme (and coding) employed in the radio system.

ie $BER = 2/\log_2 M \times SER$

where: M is the number of states in the modulation scheme.

eg For 16 QAM, M = 16 and thus

$BER = 1/2 \times SER$

The above expression assumes that 1 symbol error generates only 1 bit error, a condition achieved by using GRAY CODING on the radio system (ie adjacent symbol "words" differ by only 1 bit). Most digital radios use Gray Coding. The above expression does not take into account the effect of either "error-extension" processes, eg descrambling, or "error-reduction" processes, eg forward error correction (FEC), in the radio receiver.

NOTE: Relationships Between RF RSL and C/N Ratios
The operating range of microwave radio receivers is normally quoted in terms of RF RSL (received signal level) and not C/N or other carrier to noise units. Knowing the noise figure, F, of the radio receiver, however, the following simple relationship relates RF RSL to C/N_o (carrier to noise density) allowing the equivalent range to be quickly calculated:

$$RF\ RSL = C/N_o + F - 173.83$$

where: RF RSL is quoted in dBm
C/N_o is quoted in dBHz
F is quoted in dB

Similar relationships exist relating RF RSL to C/N and Eb/N_o, ie

$$RF\ RSL = C/N + 10 \log_{10} B + F - 173.83$$

where: C/N is quoted in dB
B is the system noise bandwidth in Hz

$$RF\ RSL = Eb/N_o + 10 \log_{10} (f_b) + F - 173.83$$

where: Eb/N_o is quoted in dB
f_b is the system bit rate in bits/s

5. NOISE AND INTERFERENCE EFFECTS IN ANALOG RADIO SYSTEMS

5.1 ANALOG RADIO DESCRIPTION

While a measure of BER is the fundamental indication of digital transmission system performance, BASEBAND SIGNAL TO NOISE RATIO, S/N_{BB} (or Noise Power Ratio, NPR), is generally regarded as being the fundamental indication of analog transmission system performance. In this Section we will thus consider the relationships between C/N_{IF} and S/N_{BB} (ie NPR) for various AM and FM analog radios. Following on from this we will then compare the various AM and FM radios on the basis of resultant S/N_{BB} for the same received carrier level.

Mathematical derivation will be kept to a minimum throughout this Section with the emphasis placed on descriptive argument. As we shall see, for most input carrier levels there exists a linear relationship between received carrier level and baseband signal to noise - ie between C/N_{IF} and S/N_{BB}. FM and Full AM analog radios, however, exhibit a so-called threshold effect where the linear relationship between C/N_{IF} and S/N_{BB} breaks down. It is important to determine at which C/N_{IF} value the threshold occurs since this is essentially the (received carrier level) operating limit of the radio. The switchover points of protection channels or threshold extension demodulators will thus be referenced to this threshold C/N_{IF} value.

Consider then the simplifed block diagram of an analog radio shown below in Fig 24.

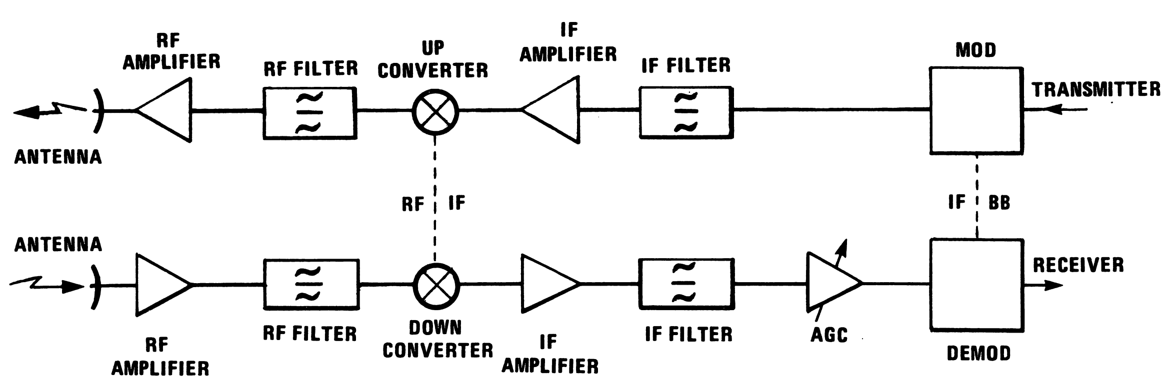


Fig 24

The simple block diagram of an analog radio above is the same as that shown in Section 4.1 for a digital radio, - ie the only major difference between the two is in the modulation/demodulation process (plus the exact filtering function). This being the case, the effects of received carrier level fading and interference in the setting-up of C/N_{IF} and C/I_{IF} ratios at the demodulator input are the same for both types of radio. The descriptions given in Section 4.1 of these processes for digital radios are thus also applicable to this Section on analog radio systems.

5.2 NOISE EFFECTS IN ANALOG RADIO SYSTEMS

5.2.1 Relationship Between C/N_{IF} and S/N_{BB} for AM and FM Analog Radio Systems

(i) FULL AM MODULATION (IE ENVELOPE DETECTION)

With Full AM the modulation process produces two sidebands (both containing the baseband signal information) and a carrier frequency component, all of which are transmitted. In the demodulation process at the radio receiver the two copies of the baseband signal contained in the modulation sidebands are effectively folded over on top of each other and add arithmetically. The noise present in each sideband is also folded over but being non-correlated adds only on a quadratic basis. A 3 dB increase in baseband signal to noise over IF signal to noise is thus the result:

ie $S/N_{BB} = 2\ C/N_{IF}$

The above expression assumes however that all of the IF carrier power is demodulated to the baseband signal. This is not the case since at best (ie for a modulation index of 1) only 1/3 of the received power is contained in the message carrying sidebands (2/3 being contained in the carrier component). Hence, at best, the demodulated baseband signal power is only 1/3 of its equivalent IF value and thus in this case:

$S/N_{BB} = 2/3\ C/N_{IF}$ FULL AM

(ii) DSBSC AM MODULATION (ie DOUBLE SIDEBAND SUPPRESSED CARRIER)

DSBSC AM modulation is very similar to full AM except that the carrier component is not transmitted - ie only the two message carrying sidebands are transmitted. This difference, however, affects only the demodulation power translation factor in the above evaluation of full AM and not the validity of the "foldover" process described. The C/N_{IF} to S/N_{BB} relationship for DSBSC AM modulation is therefore the original expression derived for full AM:

$S/N_{BB} = 2\ C/N_{IF}$ DSBSC AM

(iii) SSB AM MODULATION (ie SINGLE SIDEBAND)

In SSB AM modulation only one of the message - carrying sidebands is transmitted - ie the other sideband and carrier component are suppressed. This means that in the demodulation process only a frequency change is performed (with complete power transfer) and no foldover effects are present. Therefore:

$S/N_{BB} = C/N_{IF}$ SSB AM

(iv) FM MODULATION

In FM modulation all "major" modulation components must be transmitted for accurate reconstruction of the original message signal (ie "major" in that an FM modulated signal theoretically has frequency components extending to infinity). As a result of this, FM modulation differs from FULL AM modulation in that the IF bandwidth (B_{IF}) required for fidelity transmission is greater than twice the maximum frequency component of the baseband message signal (f_{max}). In fact B_{IF} depends on the FM modulation index, β, as well as f_{max}, (ie the greater the value of β the greater the required IF bandwidth). The relationship between C/N_{IF} and S/N_{BB} for FM modulation thus depends on the actual values of β, f_{max} and B_{IF} employed in the system. An approximate relationship is given by:

$$S/N_{BB} \simeq 3\,(\beta)^2 \frac{B_{IF}}{2f_{max}} \; C/N_{IF}$$

eg (i) $f_{max} = 3.4$ kHz; $\beta = 1$; $B_{IF} = 12.5$ kHz

$$S/N_{BB} \simeq 5.5 \; C/N_{IF}$$

ie a 7.4 dB improvement

(ii) $f_{max} = 3.4$ kHz; $\beta = 2$; $B_{IF} = 25$ kHz

$$S/N_{BB} \simeq 44 \; C/N_{IF}$$

ie a 16.4 dB improvement

Thus the "wider" the FM modulation scheme employed (ie the larger the values of β and B_{IF}) then the better is the output S/N_{BB} for any given C/N_{IF}. The penalty for this S/N_{BB} improvement however is the requirement for a wider transmission bandwidth.

NOTE: FM/FDM Systems
The above FM evaluation only applies to narrow-band (eg single channel) FM systems, where S/N_{BB} refers to the full baseband output. Similar relationships exist, however, for wideband FM/FDM systems containing many channels ; eg for a multi-channel FM/FDM system, where each channel has bandwidth b_1, the S/N_{BB} output for the highest (ie worst) channel is given by:

$$S/N_{BB} = (\beta_1)^2 \frac{B_{IF}}{2b_1} \; C/N_{IF}$$

where β_1 = modulation index of highest (worst) channel.

5.2.2 Comparison of Resultant S/N_{BB} for a given Received Carrier Level for AM and FM Analog Radio Systems

When the received RF carrier level is the same, all analog radios (having similar receiver noise figures) will set-up the same C/N_{IF} ratio at the demodulator input *assuming all employ the same IF bandwidth.*

Now for FULL AM and DSBSC AM modulation schemes both sidebands are transmitted and hence the required IF bandwidth is the same. For SSB AM modulation, however, only one sideband is transmitted and thus the required IF bandwidth in this case is only 1/2 that required for FULL and DSBSC AM systems. The noise level generated in the SSB system receiver, therefore, will be 1/2 that generated in Full AM and DSBSC AM systems. Hence for the same received carrier level:

$$[C/N_{IF}]_{SSB\ AM} = 2[C/N_{IF}]_{DSBSC\ AM} = 2[C/N_{IF}]_{FULL\ AM}$$

Substituting for the C/N_{IF} terms from the relationships derived in the last section we obtain:

For the same Received Carrier Level:

$$[S/N_{BB}]_{SSB\ AM} = [S/N_{BB}]_{DSBSC\ AM} = 3[S/N_{BB}]_{FULL\ AM}$$

ie for the same received carrier level SSB and DSBSC AM systems offer a 5 dB (approximate) improvement in demodulated baseband signal to noise ratio over a FULL AM system.

Consider now the case of FM modulation. The ratio of the FM System IF bandwidth to the FULL AM system IF bandwidth is given by $(B_{IF})_{FM}/2f_{max}$ since the FULL AM IF bandwidth is simply twice the maximum frequency of the message signal. Hence in this case for the same received carrier signal level:

$$[C/N_{IF}]_{FM} = 2f_{max}/(B_{IF})_{FM}\,[C/N_{IF}]_{FULL\ AM}$$

Substituting for the C/N_{IF} terms from the previously derived relationship we obtain:

For the same received carrier level:

$$[S/N_{BB}]_{FM} \simeq 9/2\,(\beta)^2\,[S/N_{BB}]_{FULL\ AM}$$

$$\text{eg } \beta = 2 \Rightarrow [S/N_{BB}]_{FM} \simeq 18[S/N_{BB}]_{FULL\ AM}$$

ie for the same received carrier level a narrowband FM system employing a modulation index of 2, offers a 12.5 dB (approximate) improvement in demodulated baseband signal to noise ratio over a FULL AM system.

Fig 25 below illustrates the comparison between AM and FM analog radios of S/N_{BB} vs received carrier level (ie C/N_{IF}).

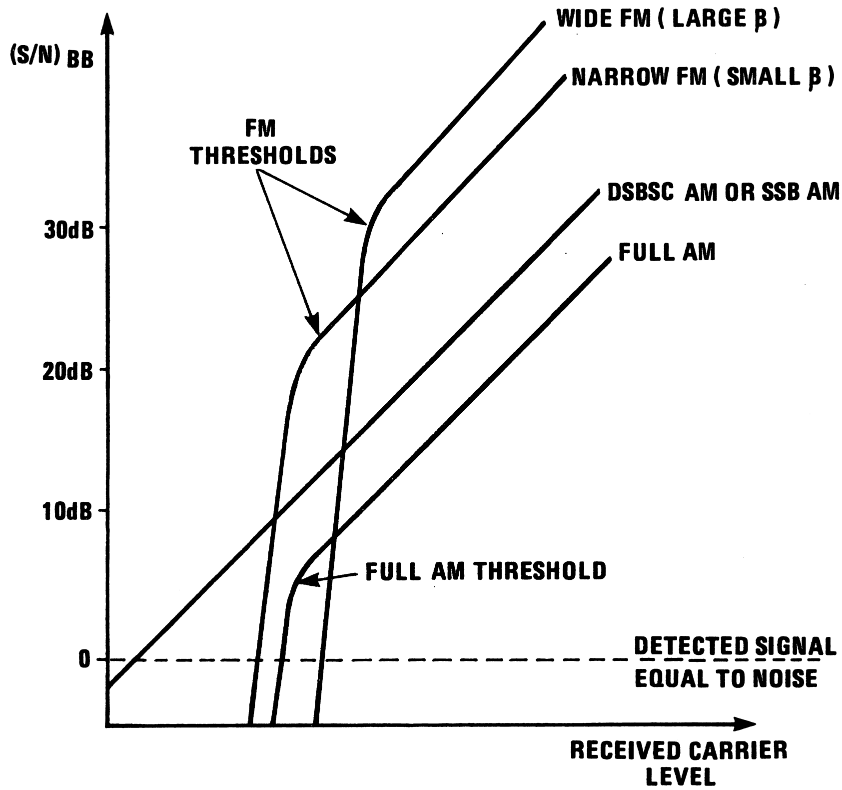


Fig 25

Labelled in the diagram are the so-called FM and FULL AM THRESHOLDS where the linear relationships between received carrier level (ie C/N_{IF}) AND S/N_{BB} seem to breakdown and the output S/N_{BB} degrades rapidly for lowering received carrier levels. This threshold effect is inherent to all NON-COHERENT demodulators such as used in FM and FULL AM radio systems (see note below).

A brief description of the threshold effect is as follows. At high received carrier levels (ie high C/N ratios) the output from a non-coherent demodulator consists of the desired signal and noise components, where these are combined on an additive basis (ie SIGNAL + NOISE). When the received carrier level falls below the threshold, however, the desired signal and noise components from the non-coherent demodulator are combined on a multiplicative basis (ie SIGNAL x NOISE). This fact results in the rapid degradation of the output S/N_{BB}.

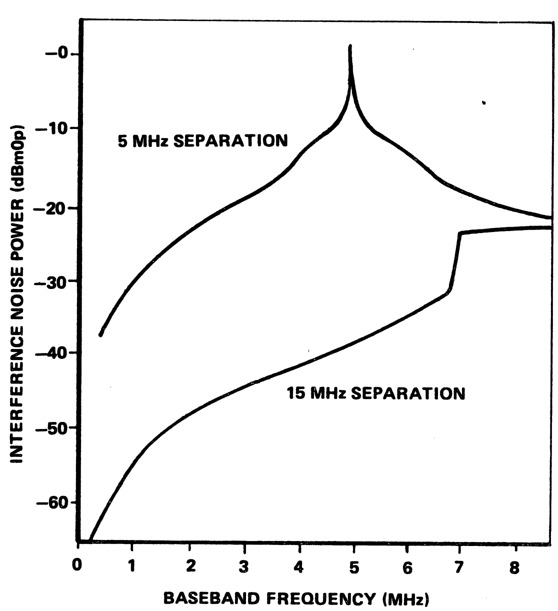
NOTE: Coherent and Non-coherent Demodulators
Non-coherent demodulators, as employed in FM and FULL AM transmission systems require no prior information about the incoming signal and can accurately recover the original baseband message signal simply from the (transmitted and hence) received signal components. Coherent demodulators, on the other hand, can not accurately recover the original baseband message signal simply from the received signal components but must insert a carrier (of correct frequency and phase) before demodulation can be performed. Coherent demodulators are required in suppressed carrier transmission systems such as DSBSC AM and SSB AM.

5.3 INTERFERENCE EFFECTS IN ANALOG RADIO SYSTEMS

Any interference signals present at the input to an analog radio demodulator will almost certainly cause distortion of one form or another on the reconstructed baseband message signal. The type of distortion introduced will depend on many factors including the type of demodulator and the characteristics of the desired and interfering signals. The most common form of distortion introduced is where the demodulated interference appears as additional baseband noise on the desired signal. This, for example is the effect of analog/digital interference on an FM/FDM analog radio.

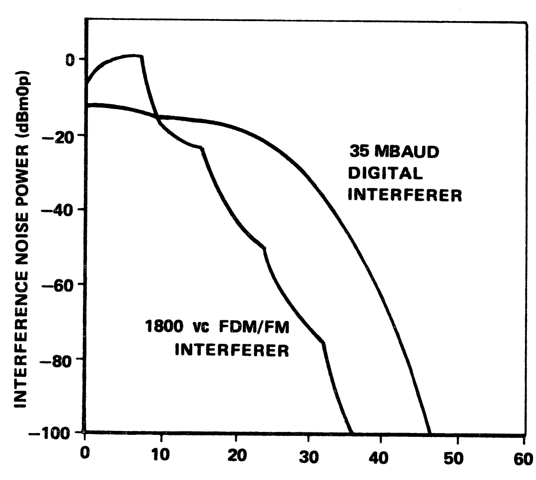
Fig 26a illustrates how the "interference noise power" varies across the baseband spectrum of an 1800 voice circuit (vc) FDM/FM signal. The interfering signals are other 1800 vc FDM/FM signals of the same power and with centre RF frequency separations of 5 MHz and 15 MHz. Note that at centre frequency separations below the top baseband frequency the worst affected voice circuit lies where the interfering carrier component falls. At centre frequency separations greater than the top baseband frequency the top voice circuit experiences most interference.

When "interference noise power" into the worst affected voice circuit is plotted against RF interferer separation, Fig 26b results. Here the wanted signal is again an 1800 vc FDM/FM signal while the interferers are another 1800 vc FDM/FM analog signal and a 35 MS/s digital signal, both of the same received power as the wanted signal.



INTERFERENCE BETWEEN TWO 1800 vc FDM/FM SIGNALS

Fig. 26(a)



INTERFERENCE INTO 1800 vc FDM/FM SIGNAL

Fig. 26(b)

Fig 26

6. COMPARISON BETWEEN HP 3708A METHOD AND TRADITIONAL METHOD OF C/N TESTING

6.1 TRADITIONAL METHOD OF C/N TESTING

The traditional method of C/N testing involves the use of variable RF (normally waveguide) attenuators to attenuate the incoming RF carrier (as happens during a true fade). By then performing power measurements of the resultant IF carrier and noise levels the C/N ratio set-up may be determined. Note that the noise power measurement should be made via a band-defining filter having a noise bandwidth equivalent to the (double-sided) system noise bandwidth. If the system noise bandwidth, however, is determined by the radio IF filter (as is the case for most analog radios) then performing the noise measurement at a point *after* this filter removes the requirement for the (external) bandpass filter at the power meter input. The strength of this traditional method is that it simulates exactly what happens when a true flat fade occurs in practice and checks not only the receiver demodulator "noise margin" but also the capability of the complete receiver to process low received carrier levels. (See Section 6.4 for more details.)

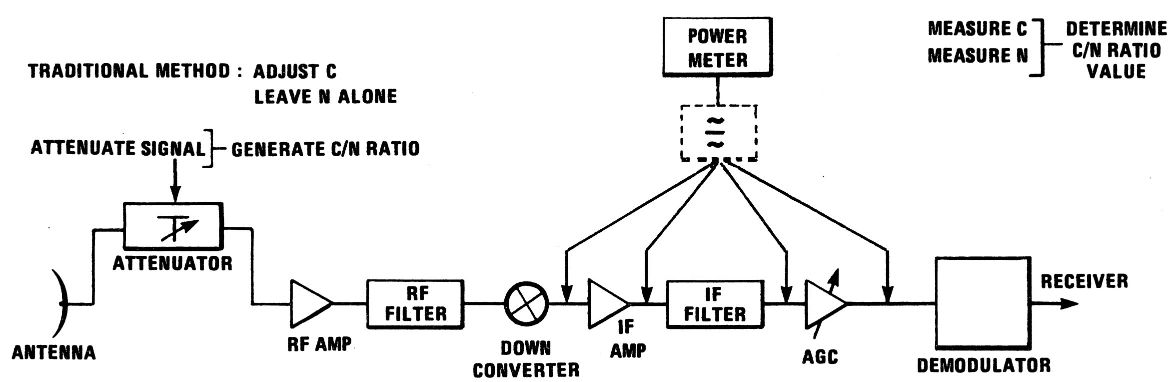


Fig 27

6.2 HP 3708A METHOD OF C/N TESTING

The HP 3708A method of C/N testing involves the injection of noise of known spectral density into the IF section of the radio under test. By monitoring the received carrier level (and not adjusting it in any way) the appropriate noise level is then injected to set-up the desired C/N ratio. (See Fig 28). In the HP 3708A TRACKING mode, the injected noise level is continuously updated in response to measured carrier level variations, thereby maintaining the accuracy of the generated C/N ratio at all times. (See Section 6.4 for more details.)

As shown in the diagram, the HP 3708A may be used at any point in the radio receiver IF chain. The object must always be, however, to allow the system under test to determine the bandwidth of the injected noise and the C/N ratio to be defined in this bandwidth. The SYSTEM BANDWIDTH and EXTernal FILTER facilities on the HP 3708A should ensure that this can be achieved in most cases. (See Product Note 3708-2 (Publication Number 5953-5489) for a detailed description on how to achieve this objective.)

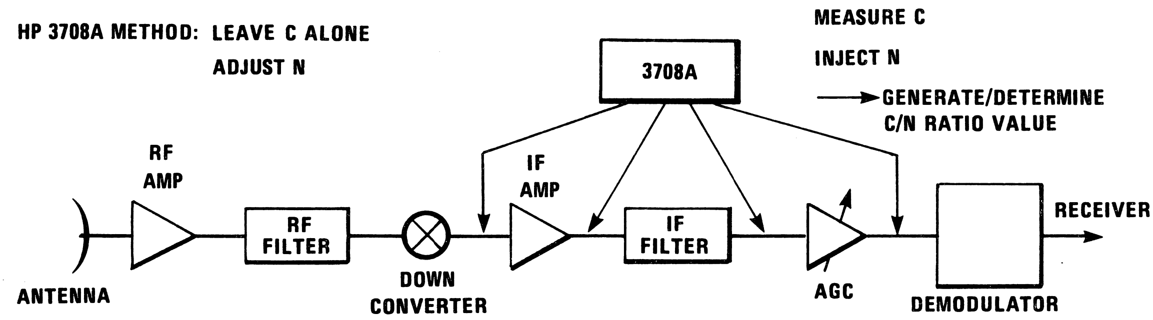


Fig 28

6.3 CRITICAL FACTORS OF THE HP 3708A METHOD

(i) FINITE CREST FACTOR OF GAUSSIAN NOISE SOURCE

The crest factor of a waveform is the ratio of the peak voltage to the RMS voltage. Naturally occuring (Gaussian) noise is of infinite crest factor - ie there is a small but finite chance that a noise peak as high as 10 x , 100 x... the RMS value will occur. Man-made Gaussian noise sources, on the other hand, are limited by their amplification processes to a finite crest factor. A crest factor of 15 dB (which limits voltage peaks to 5.6 times the RMS value) is generally regarded as being the minimum acceptable for good Gaussian noise simulation. This allows digital radio noise-induced error ratios of down to at least 10^{-8} to be simulated. The HP 3708A crest factor (specified as >15 dB) is typically >20 dB allowing accurate measurement down to 10^{-12} BER.

(ii) CALIBRATED NOISE DENSITY

For operation in C/N_0 and Eb/N_0 modes where the noise level is set-up in terms of a density (and also for the SYSTEM BANDWIDTH facility in C/N mode) it is important to ensure that this noise density is accurately calibrated. In the HP 3708A this is achieved by measuring the noise bandwidths of the internal, band-limiting filters for every instrument during manufacturing, and storing these personalised values in each instrument's non-volatile memory.

(iii) RADIO INTRINSIC NOISE COMPENSATION

The HP 3708A method of C/N testing involves the injection of calibrated noise to set-up an operator selected C/N ratio. The radio receiver itself however also generates noise which is added to the desired signal (ie an intrinsic C/N ratio exists). For most cases the noise being injected by the HP 3708A will be much greater than the radio intrinsic noise and hence this latter term may be neglected. There are instances, however, where the intrinsic radio noise will be of comparable level to that of the HP 3708A injected noise,

eg (i) where a high C/N ratio is selected on the HP 3708A
(ii) where the measured carrier value (C) is very small (as is the case in satellite systems).

In these cases, the radio intrinsic noise needs to be compensated for when setting HP 3708A C/N ratios. The following expression relates $(C/N)_{ENTERED}$ to $(C/N)_{DESIRED}$ and $(C/N)_{INTRINSIC}$ (where all the C/N ratios are quoted in dB's):

$$(C/N)_{ENT} = 10\log_{10}\left[1 + 10^{-\frac{(C/N)_{INT}}{10}}\right] - 10\log_{10}\left[10^{-\frac{(C/N)_{DES}}{10}} - 10^{-\frac{(C/N)_{INT}}{10}}\right]$$

eg For $(C/N)_{DES}$ = 10 dB and $(C/N)_{INT}$ = 13 dB the value of C/N that should be entered on the HP 3708A is 13.23 dB, ie $(C/N)_{ENT}$ = 13.23 dB.

The $(C/N)_{INTRINSIC}$ value may be calculated from the following expression:

$$C/N_{INTRINSIC} = \frac{RSL_{IF}}{F\,k\,T_O\,B(G_{RF})}$$

where RSL_{IF} = Received IF signal level (ie measured immediately after RF/IF down converter)

$F\,k\,T_O\,B\,(G_{RF})$ = Receiver nominal RF noise level

Appendix A contains curves detailing $(C/N)_{ENTERED}$ vs $(C/N)_{DESIRED}$ for various $(C/N)_{INTRINSIC}$ values. Note, however, that the $(C/N)_{INTRINSIC}$ value varies in accordance with the received carrier level and hence some inaccuracy may be introduced into the C/N ratio set-up, if the HP 3708A and radio noise levels are such (or become such) that a compensation factor is required. It is expected, however, that radio intrinsic noise compensation will only be required for satellite systems where the received carrier levels tend to be relatively stable (and not for *terrestrial* systems where received carrier level variations are more common).

6.4 ADVANTAGES OF TRADITIONAL METHOD VS HP 3708A METHOD

(i) COMPLETE RADIO RECEIVER CHECK

As stated before, the traditional method of C/N testing checks not only the noise margin of the demodulator (as does the HP 3708A method) but also the capability of the radio receiver (RF and IF sections) to process low received carrier levels.

To comprehend how advantageous this fact is, consider the following list of equipment factors (ie excluding propagation phenomena like interference) that contribute to the overall flat fading performance of a microwave radio receiver:

(a) The noise margin of the stand-alone (BB) demodulator.

(b) The radio (IF/BB) filtering and equalisation design which reduces the noise margin of the demodulator from its stand-alone value.

(c) The capability of the IF AGC amplifier to present the demodulator input with a (distortion-free) carrier signal of the proper level.

(d) The noise output level from the radio receiver RF section.

Using the HP 3708A method of C/N testing on a radio modulator/demodulator looped back to back allows the effect of (a) to be determined. The same test on a radio transmitter/receiver looped back either remotely at RF or locally at IF (immediately after the down-converter) allows the effect of (a) and (b) together to be determined. With this same configuration but an IF attenuator included before the AGC, the combined effect of (a), (b) and (c) may be determined - ie measure the demodulator noise margin for different settings of the attenuator to check for any deviation due to factor (c). (See Fig 29.) The only restriction on this test may occur at maximum AGC gain settings where the AGC noise figure may become significant. This, however, can be compensated for in a similar manner to that described in Section 6.3 (iii) for the radio RF intrinsic noise. The HP 3708A C/N test method does not allow, however, the effect of (d) to be determined.

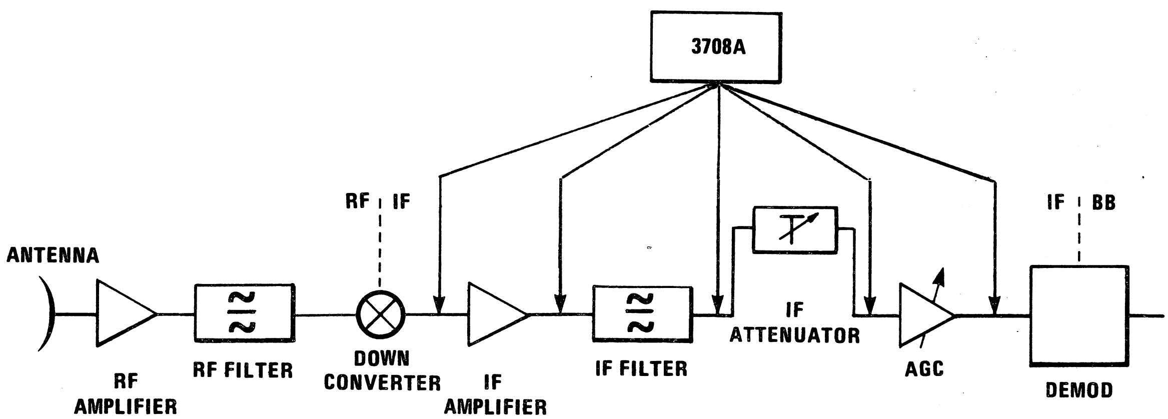


Fig 29

The traditional method of C/N testing allows the combined effect of (a), (b), (c) and (d) to be determined. This, however, is the only test possible with this method.

Thus, for a complete check of the radio performance during flat fading conditions, the traditional method of C/N testing is required. Factor (d), however, can easily be checked at sub-assembly (or system) level via a simple noise figure measurement on the RF components (or complete radio receiver).

Factors (a), (b) and (c) are thus generally regarded as the most important to be checked and the HP 3708A method, therefore, considered as a valid test of radio system performance. This method also allows the effects of (a), (b) and (c) to be determined separately - an important capability for radio designers.

(ii) EQUIPMENT COST

Obviously, the equipment cost for the traditional method is much less than for the HP 3708A method. This equipment premium is more than offset, however, by the advantages of the HP 3708A method (listed in the next Section) some of which may be directly related to cost savings; eg increased measurement throughput reducing labour costs and/or the required number of test-stations.

6.5 ADVANTAGES OF THE HP 3708A METHOD VS TRADITIONAL METHOD

(i) EASE OF USE / MEASUREMENT SPEED

TRADITIONAL METHOD - the traditional method is certainly not easy to implement with the insertion of the RF attenuator normally involving climbing to the top of the radio rack and physically bolting in an appropriate waveguide section. There are further difficulties involved when attempting to automate C/N testing using this method.

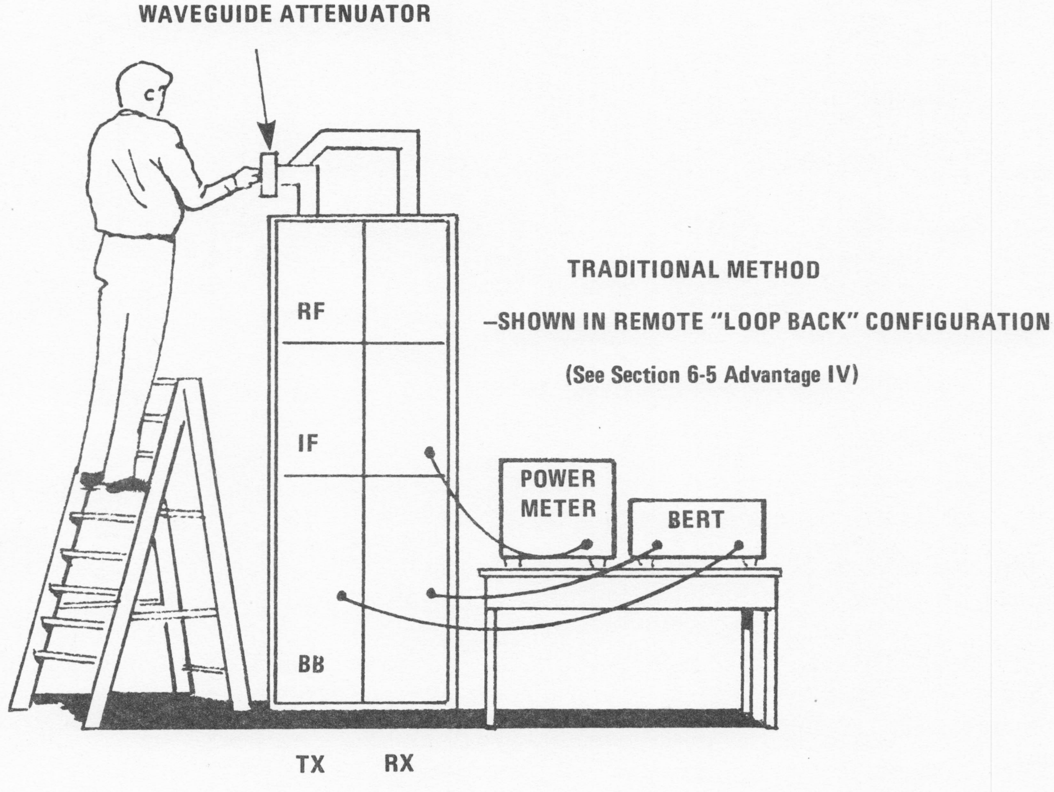


Fig 30

HP 3708A METHOD. The implementation of the HP 3708A method of C/N testing is obviously much simpler than the traditional method requiring only cabled connections to and from any point in the IF section of the radio. C/N ratios can then be set simply at the press of a key. Where automated C/N testing is required the HP 3708A offers complete programmability via HP-IB and indeed with the introduction of the HP 3708S (the associated software system of the HP 3708A) automated C/N testing of digital radios is available today (see HP 3708S Data Sheet for details - Publication Number 5953-5470).

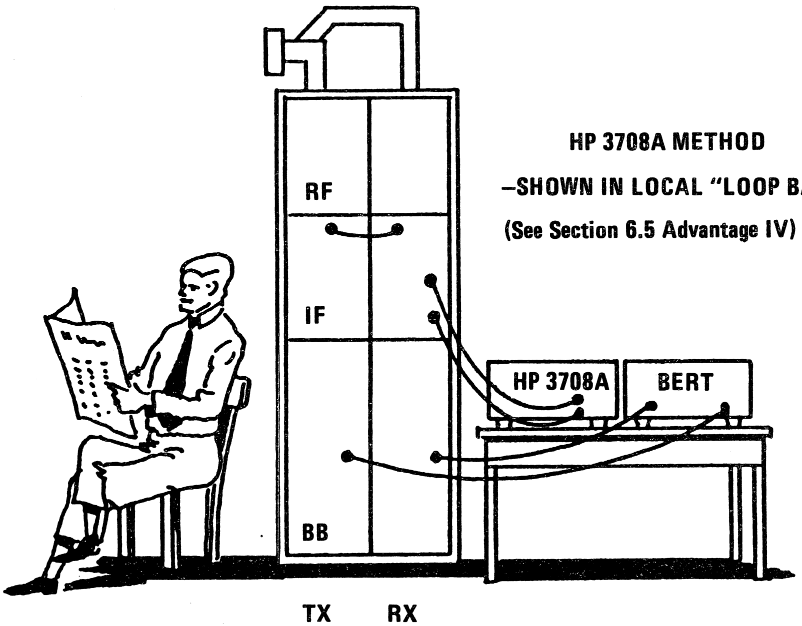


Fig 31

To obtain some indication of the increased measurement throughput obtained from the HP 3708A method, consider the typical times required to perform the following measurements, as presented below:

- 10 measurements (ie C/N vs BER curves), each consisting of 10 points, where the BER result is averaged over two 10 second gating periods,

(i) where the 10 measurements are performed on the same radio (eg during the commissioning of a new link)

(ii) where the 10 measurements are performed on 10 different radios (eg on a radio system production line)

	(i)	(ii)	IMPROVEMENT	
TRADITIONAL METHOD	3hrs 55mins	6hrs 10mins	x 3	x 6
HP 3708A MANUALLY	1hr 15mins	2hrs -		
HP 3708S SYSTEM	- 44mins	- 53mins	x 2	

Note: Figures quoted for the traditional method are unlikely to be attained on testing carried out under field operating conditions where tests may end up being aborted (see next Section).

(ii) ACCURACY

TRADITIONAL METHOD - The actual C/N ratio may vary while performing the digital radio BER or analog radio S/N_{BB} measurement due to natural variations in the received carrier level (ie atmospheric attenuation of the RF signal) in addition to the artifically introduced attenuation. (See Fig 32.)

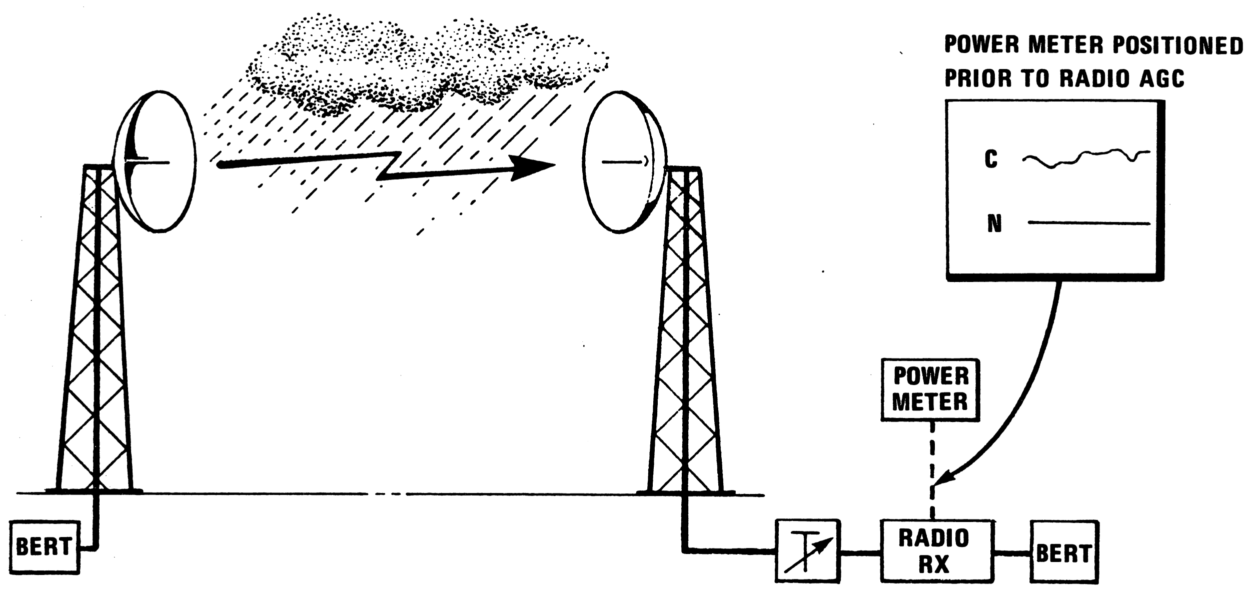


Fig 32

The C/N value set-up by the use of the waveguide attenuator and determined by the power measurement(s) will only be maintained so long as the received carrier level remains at the same value as when the power measurement(s) were taken. In an operational situation (ie in the field) this will almost certainly not be the case since the received carrier level will be continuously varying due to atmospheric effects. As a change in the C/N ratio of <1 dB can result in an order of magnitude change in the measured BER for a digital radio, the accuracy of the C/N ratio is obviously an important parameter. Furthermore if the waveguide attenuation is such that the received carrier level is near to the minimum detectable by the receiver any further attenuation due to atmospheric conditions can result in the radio crashing and the C/N test being aborted.

HP 3708A METHOD - Where the HP 3708A is positioned prior to the AGC, accuracy of the selected C/N ratio is maintained by continuously monitoring the incoming IF carrier level and adjusting the injected noise level to compensate for variations in the measured carrier; ie CARRIER "TRACKING" MODE (see Fig 33). Received carrier level fluctuations due to atmospheric effects do, therefore, not alter the C/N ratio from the selected value and the accuracy of the C/N vs BER or S/N_{BB} plot is ensured. (N.B. Where the IF access is obtained after the AGC the IF carrier level should remain constant and the tracking capability of the instrument not then required).

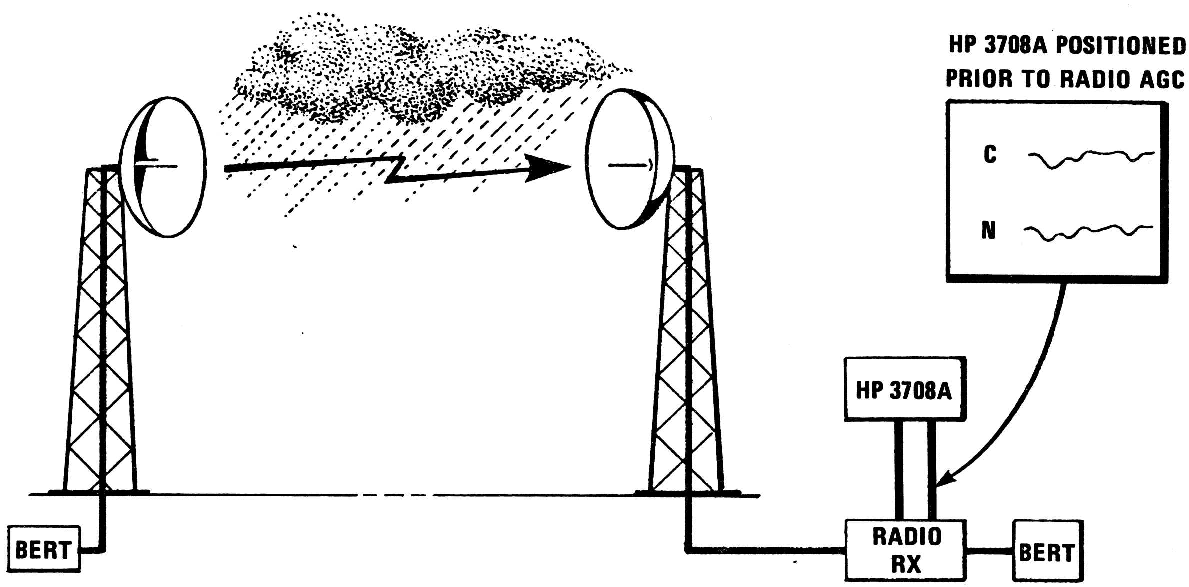


Fig 33

(iii) FAULT FINDING

As explained in Section 6.4 (i), there are four (major) equipment factors which contribute to the flat fade performance of a microwave radio. The traditional method tests the composite effect of all four factors. If, however, the measured performance is sub-standard, this method is of no use in tracing the fault to one (or more) of the factors. Now, factor (d), as stated before, may be individually checked by another relatively simple test, but this still leaves factors (a) and/or (b) and/or (c) as the potential source of the problem. Using the HP 3708A method, the individual effects of (a), (b) and (c) may be determined (as explained in Section 6.4(i)), thereby allowing the fault to be traced to the individual factor(s).

(iv) RADIO RACK TESTING

The transmitter (TX) and receiver (RX) sections contained in the one radio rack normally employ different RF frequencies (neighbouring hops using different frequencies to reduce the possibility of interference). Thus, when testing using the traditional method (requiring RF transmission), a minimum of two radio racks are required unless the signal is looped back at some remote site. With the HP 3708A method, however, the radio may be locally looped back at the IF stage and thus the TX and RX sections from the same rack tested together more simply.

6.6 OBTAINING SIMILAR RESULTS USING THE TRADITIONAL AND HP 3708A METHODS OF C/N TESTING

As stated previously, the traditional method of C/N testing involves the measurement of the carrier and noise levels. If performed correctly, the noise power measurement should be performed in one of three ways :

(i) In cases where the system noise bandwidth is determined by baseband filtering, via a bandlimiting filter of noise bandwidth equivalent to the double-sided (ie IF) system noise bandwidth.

(ii) In cases where a comparison of practical versus theoretically possible performance is desired via a bandlimiting filter of noise bandwidth equivalent to the (double-sided) Nyquist bandwidth. (See Section 4.4.2.)

(iii) In cases where the system noise bandwidth is determined by the IF filter at a point after this filter (ie on the baseband side).

To achieve the same results using the HP 3708A for each of the traditional method procedures the following techniques respectively should be used :

(i) Position the HP 3708A at any point in the radio IF section with the system noise bandwidth value entered as the SYSTEM BANDWIDTH.

(ii) Position the HP 3708A at a point prior to the system bandwidth determining filter (which will either be at baseband or IF) and enter the double-sided Nyquist bandwidth value as the SYSTEM BANDWIDTH.

(iii) Position the HP 3708A prior to the IF filter and enter the system noise bandwidth as the SYSTEM BANDWIDTH.

In cases where the IF filter determines the system noise bandwidth and access is not available prior to this component the EXTernal FILTER facility on the HP 3708A (along with an identical IF filter) should be used to achieve the same results. Product Note 3708-2 (Publication Number 5953-5489) discusses in more detail how to use the "SYSTEM BANDWIDTH" and "EXT FILTER" facilities on the HP 3708A to perform C/N testing.

To summarize then on how to obtain the same results from both methods (see Fig 34) :

* Ensure that both measurements are referenced to the same carrier term (eg the modulated IF signal level or unmodulated IF carrier level).

* Position the HP 3708A prior to the radio IF filter and enter the appropriate value as the SYSTEM BANDWIDTH ie the system noise bandwidth or the double-sided Nyquist bandwidth.

* Ensure that the internal noise filter selected on the HP 3708A is wider than the noise bandwidth of the system under test.

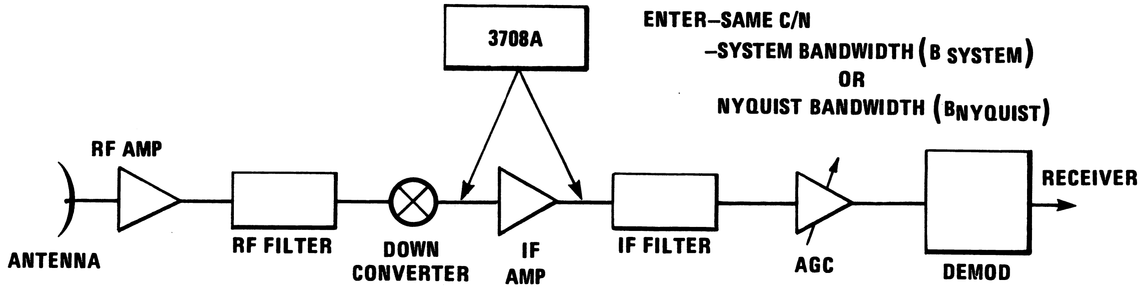


Fig 34

6.7 HP 3708A METHOD OF INTERFERENCE TESTING

Traditionally, the addition of an interference signal into a radio receiver involved the use of RF or IF couplers. Setting of the desired C/I ratio then required the adjustment of the (external) interference signal source to generate the desired C/I ratio at the demodulator. Interference tests could then be performed either in conjunction with RF waveguide attenuation (to simulate received carrier fading),

- ie C/N WITH FIXED I vs BER (or S/N_{BB})

or at normal received carrier levels

- ie C/I vs BER (or S/N_{BB})

The HP 3708A includes facilities to simulate both types of interference test described above:

(i) The "AUX I" input on the rear panel of the instrument allows C/N testing to be performed in the presence of an additional interference signal (eg C/N with fixed I vs BER). The HP 3708A performs no processing on this interference signal (but there is a 15 dB loss to the injection point) and thus the "AUX I" signal strength must be set to the desired level at the signal source. Note also that in TRACKING mode if the desired signal level ("C") changes, only the injected noise level is adjusted by the HP 3708A to compensate and not the "AUX I" level; ie the I level remains fixed, not the C/I ratio.

(ii) The "C/I" mode of the instrument allows interference measurements to be performed without the additional injection of noise (eg C/I vs BER). In this mode the interference signal is supplied to the HP 3708A front panel "I" input connector (see Fig 35, below) at a fixed level of (approximately) -29 dBm. The HP 3708A then internally adjusts the level of the "I" signal to set-up any operator selected C/I ratio. Note that in this mode the "TRACKING" facility automtically adjusts the "I" level to compensate for any variations in the received carrier level "C"; ie the C/I ratio remains fixed. As mentioned in Section 4.4.2, one important use for the C/I mode of the HP 3708A is in the prediction of residual BER on digital radio systems. See Product Note 3708-3 (Publication Number 5953-5490) for more details on this measurement.

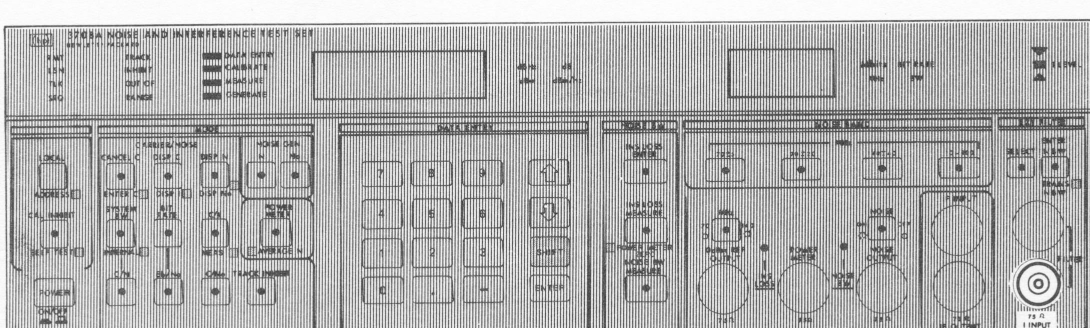
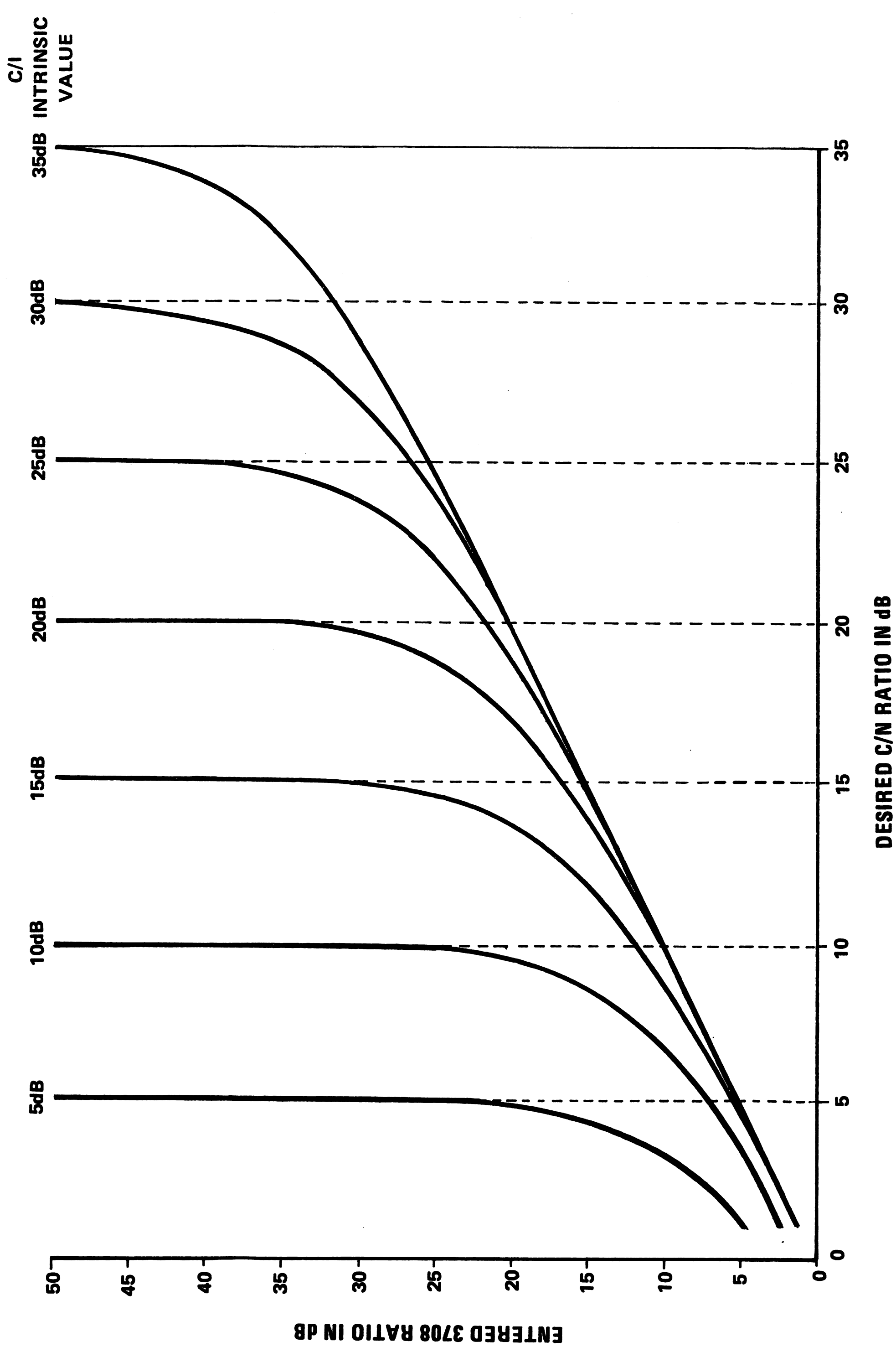


Fig 35

APPENDIX A: COMPENSATION FOR INTRINSIC RADIO NOISE WHEN SETTING HP 3708A RATIOS



Notes

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